Radiant heat attenuation by clothing
and
Human tolerance to radiant heat:

Field experiments with LNG fires

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13. ABSTRACT (Maximum 200 words)

A series of tests involving the exposing mannequins clothed with normal civilian clothing to a 10 ft x 10 ft LNG pool fire was conducted. Both single layer clothing and double layer clothing were used. The radiant heat flux incident outside the clothing and incident on the skin covered by clothing were measured using wide-angle radiometers, for durations of 100 s to 200 s (per test). The levels of heat flux incident on the clothing were close to 5 kW/m^2. The magnitude of the attenuation factor (AF) (ratio of the outside radiant heat flux to that on the skin) was calculated. It is seen that AF varies between 2 and higher for ordinary cotton and polyester clothing (of thickness 0.286 mm to 1.347 mm). Values as high as 6 have been measured for clothes of thickness 1.347 mm.

Tests similar to the above were conducted to determine the attenuation factor when a single or multiple sheets of newspaper are interposed in front (about 5 cm) of the radiometer. Singe sheet newspapers reduce the heat flux to the radiometer by a factor of about 5 at a heat flux level of 5 kW/m^2. Double sheets reduce the heat flux intensity by a factor of almost 8! The magnitude of the AF for newspaper sheets depends on the magnitude of the heat flux and thickness. It decreases linearly with increasing heat flux values and increases linearly with increase in thickness.

The author exposed himself, in normal civilian clothing (of full sleeve cotton/polyester shirt and jean pants) to the radiant heat flux from the LNG fire at levels of 4 7 kW/m^2 and higher for tens of seconds; Occasionally, as high as 7 kW/m^2 for durations of several seconds. He did not suffer any injury, burns or skin blisters for exposure times ranging from 25 s to 97 s at average heat flux values of 4 kW/m^2 to 5 kW/m^2. The incident heat flux on the author was measured by a handheld radiometer with a display and later by wide-angle radiometers (whose output was recorded on a computer) strapped on to him. The results indicated that he could withstand the regulatory criterion of 5 kW/m^2 for 30 seconds without suffering any damage or burns. Temperature measured on the skin of the author covered by the clothing did not rise above the normal body temperature even after 200 s of exposure to an average heat flux of 4 kW/m^2.

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The field test facility of the Commonwealth of Massachusetts, Department of Fire Services (DFS) at Stow, MA was used in conducting the LNG fire tests. The author expresses his thanks to the officials at DFS who permitted, with enthusiasm and encouragement, the performance of these tests at the Stow facility. In particular, Dr. Raj acknowledges with thanks the support and active interest in the project shown by the following officers at DFS.

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2 Mr. Thomas Leonard, Dy. Fire Marshall
3 Mr. Kevin Partridge - Director, Emergency Response & Homeland Security
4 Laurent (Larry) McDonald - Director, Massachusetts Firefighting Academy
5 Richard Farrar - Acting Deputy Director, Massachusetts Firefighting Academy

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1 Norman Seymour
2 Jack Joyce
3 Stephen Corbett
4 Dick Shafer
5 Tim Choate
6 Mike Gurnick

The concept of conducting a series of measurements with the LNG fires that were to be used in a firemen training course came from Chief David Butler, and Capt. Mike Nigro of

Everett Fire Department. The author thanks Chief Butler and Capt. Nigro for permitting interruptions to the firemen training and allowing us to set up the instruments and gather the data on radiant heat fluxes and the effectiveness of clothing in attenuating the radiant heat.

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Executive Summary

E.1 Background and the need for the experiments

The criteria presented in the LNG hazards assessment literature on hazards to people from exposure to radiant heat from fires are based on small scale, laboratory type experiments. Most of the testing has been on dead skins, artificial skin simulants and on pigs. In only one documented experiment was there any testing with live human beings (wherein volunteers were exposed in a laboratory to heat from a small quartz lamp over a very small area on the forearms). There have been no large scale, field type of tests in which human beings in their normal clothing have been subject to radiant heat fluxes from real fires and their effects measured. Yet these laboratory and very small scale criteria, and especially the criterion on skin burn in human beings exposed for 30 seconds to a radiant heat flux of 5 kW/m^2 (or 1600 Btu/hr ft^2), have been adopted by industry standards (such as the NFPA 59A, API, etc) and in US regulations applicable to liquefied natural gas (LNG) facility siting (49 CFR, Par 193). Without large-scale test data obtained under conditions normally prevalent in an accident situation the correctness of the use of these hazard criteria are to be questioned. In addition, the policy implications of the regulations and the standards, which require calculation of exclusion zones (from fire exposures) using these criteria obtained under ideal conditions in a laboratory, are significant.

Neither the industry standard, NFPA 59A nor the US federal regulations take into account in the required exclusion zone calculations some of the realistic conditions that exist around LNG facilities and the effect of some of these conditions. For example, no considerations are given to the effectiveness of clothing on people or the effect of obstructions (buildings, structures, and other objects) in attenuating the radiant heat flux from a fire. This may be due to the lack of field data on such effects.

Therefore, and with a view to obtaining baseline data on several issues related to exposure of people to LNG fire radiant heat, Technology & Management Systems, Inc., undertook a series of tests in the field with 3 m x 3 m (10 ft x 10 ft) size LNG fires. The tests were jointly sponsored and supported by the Pipeline and Hazardous Materials Safety Administration ("PHMSA") of the US Department of Transportation and Distrigas of Massachusetts Corporation, LLC ("DOMAC").

E.2 Test objectives

Tests were designed and conducted to determine the following.

1 The effectiveness of ordinary civilian clothing, both single layer and multi layer, in attenuating the radiant heat flux from a LNG fire, at a level of 5 kW/m^2 (1600 Btu/hr ft^2). That is, to determine the fraction of the heat flux incident on the clothing that actually reaches a person's skin covered by the clothing.

2 The reduction in the heat flux reaching a person when shaded by simple objects such as a thin newspaper sheet held in front.

3 The level of heat flux that a human being, dressed in normal civilian clothes, can withstand without significant pain or suffering skin burn injury, and the duration over which such heat fluxes can be withstood.

Although the 3rd objective was not part of the original design of the tests, the project manager (and author of this report) utilized the opportunity to volunteer and test the adequacy and validity of current correlations in the LNG hazards literature on the degree of tolerability to radiant heat fluxes and the duration of safe exposure without suffering skin burns.

It is noted that only a part of the energy in the radiant heat flux incident on a human skin is actually absorbed (or transmitted through the thickness of the skin to the blood vessels). A fraction close to 35% gets reflected and scattered, irrespective of the visual color pigmentation (white, black, brown, etc). The magnitude of the fraction absorbed depends upon the moisture content of the skin (the higher the moisture content the greater the absorption) and the spectral distribution of energy in the incident radiation. If, for example, the radiant heat energy originating from a fire (including an LNG fire) has traveled significant distance (greater than 100 m) and the atmospheric relative humidity is high (> 50%) then it is known that a substantial part of the radiant energy is absorbed by the moisture in the atmosphere and the energy spectrum incident on the skin will be devoid of the energy in the water vapor bands. Since the skin absorbs preferentially in the water vapor bands, the absence of energy in these bands implies that the skin would absorb a smaller fraction of the incident energy, even if the total radiant heat flux falling on the skin is 5 kW/m^2. The higher the wind speed the greater is the cooling of the skin and, therefore, the greater is the time for the skin temperature to reach the critical (burn) temperature for a given incident heat flux level.

Figure E-1: Overall view of the test facility showing the dike, the LNG fill-pipe and the observation tower

E.3 Test details

A series of tests was performed with LNG pool fires in a 3 m x 3 m x 0.53 m depth (10 ft x 10 ft x 21 inches) dike made of concrete floor and wet sand sides. The field test facility of the Commonwealth of Massachusetts, Department of Fire Services at Stow, MA was used to conduct the experiments. The tests were run between September and November 2006. Figure E-1 shows the general view of the test facility.

Three types of tests were conducted in this series, namely,

(i) Exposure of clothed mannequins (a male and a female) to LNG fire radiant heat. The mannequins were instrumented with radiometers located outside the clothing and inside the clothing. Also thermocouples were provided to measure the atmospheric temperature close the mannequins, just above the outer shirt and on the skin of the mannequins.

(ii) Interposition of newspaper sheets (of one sheet and two sheet thickness) about 5 cm (2 inches) in front of the outer radiometer of one of the mannequins while the radiometer of the other mannequin was not obstructed. (Both mannequins were next to each other at the same distance from the dike center).

(iii) Exposure of the author (Dr. Raj) in civilian clothes to the LNG fire radiant heat by his movement towards the fire until the handheld radiometer indicated heat flux levels 5 kW/m^2 or higher. The duration of time that the author could withstand the radiant heat at that location without suffering pain or skin burn injury was noted[1].

Figure E-2 shows the two fiberglass mannequins used in the tests. Figure E-3 shows the author using the handheld radiometer and approaching the fire.

The clothing on the mannequins and on the human subject consisted of both cotton apparel (outside shirt and undershirt), as well as polyester & cotton (65% & 35 %, respectively) mixed outer shirt. The radiometers used were all of the wide-angle type. In general, the mannequins were located at such a distance from the dike center that the heat flux was about 5 kW/m^2. Of course, the instantaneous heat flux varied (in some instances significantly) due to the flame bending by the wind in different directions. The heat flux values were recorded at 0.1 s intervals of time. Tests involved duration of exposures ranging from 60 s to 300 s. A total of 16 tests (exposure trials) were conducted with mannequin exposure. In 8 of theses tests, newspaper sheets were held in front of one of the mannequins for sufficiently long time (ranging from 30s to 100 s) to determine the heat flux attenuation by the newspaper sheets.

1 In none of the tests did the author suffer any injury of even severe "burn" pain. In addition, he was always accompanied on the side by a fireman in full bunker gear to provide assistance in case of need, which never occurred.

Figure E-2: Picture shows the mannequins used in the tests and their clothing

Figure E-3: The author facing the fire in civilian clothes. The handheld radiometer indicates the heat flux level to which he is being exposed

On 16 instances the author approached the fire with the handheld radiometer. The heat flux values displayed on the handheld radiometer screen were noted. The handheld radiometer did not have the proper connection to record the data on a computer. The duration of time over which he was exposed to the fire at the particular level of heat flux was obtained later from video films of the tests. In subsequent 4 tests, the author used one of the more sophisticated radiometers from the mannequins and recorded digitally the exposure heat flux data on to a computer. Because of the wind effects on the fire and the constant shifting of the fire plume towards and away from the author, it was difficult for him to maintain the same exposure radiant heat flux level, even though he tried to move back and forth trying to be in sync with the fire plume.

E.4 Principal results

Attenuation of radiant heat flux by clothing

A typical data recording from one of the tests is indicated in Figure E-4. This figure shows that heat flux level outside the location of the mannequin, the radiometer reading inside the clothing and the attenuation factor (defined as the ratio of the outside heat flux to the heat flux after passing through the clothing) are shown plotted as a function of time. It is seen that in this case the attenuation factor (AF) is about two for the case when the view of the inner radiometer is through the thin parts of the outer and inner shirts. Similar data have been obtained for other conditions (of clothing thickness), exposure heat flux magnitude and duration.

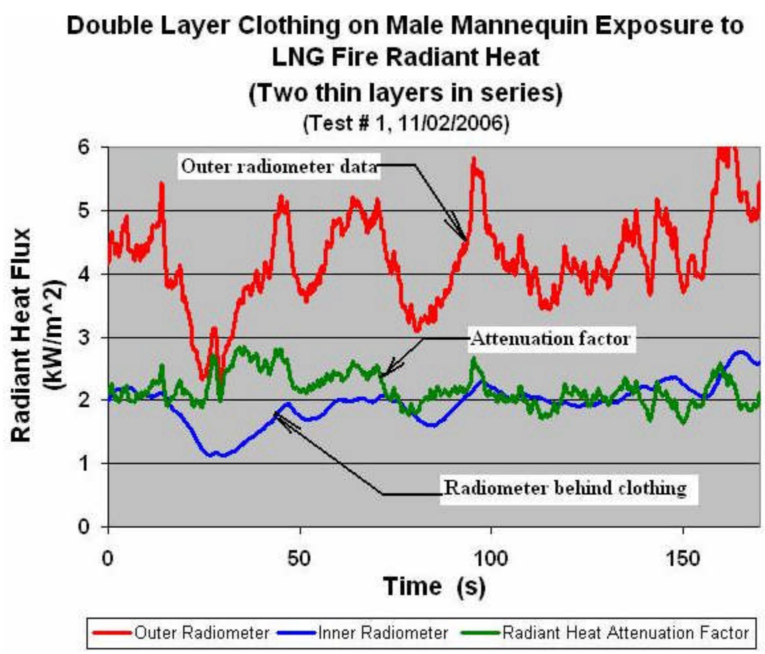

Figure E-4: A sample record of radiometer data from the male mannequin

The overall result from the clothing exposure tests indicate that normal civilian clothing provides a significant reduction in the magnitude of the heat flux reaching the skin (covered by the clothing). This reduction factor can be between 2 and 3, even though in some cases factors as high as 6 and 7 have been measured at exposure levels close to 5 kW/m^2. Figure E-5 shows the overall results from the clothing exposure tests showing the relationship between the attenuation factor and the nominal thickness of the clothing (nominal thickness does not include the thickness of the air gap between the inner and outer clothing).

Newspaper sheet effectiveness

It is seen that even a single sheet of newspaper attenuates the magnitude of the radiant heat flux by a significant factor. Figure E-6 shows a typical radiant heat flux record of the same radiometer without any obstruction and with a single sheet newspaper in its front at about 5 cm (2 inch) distance. The dramatic reduction is quite evident.

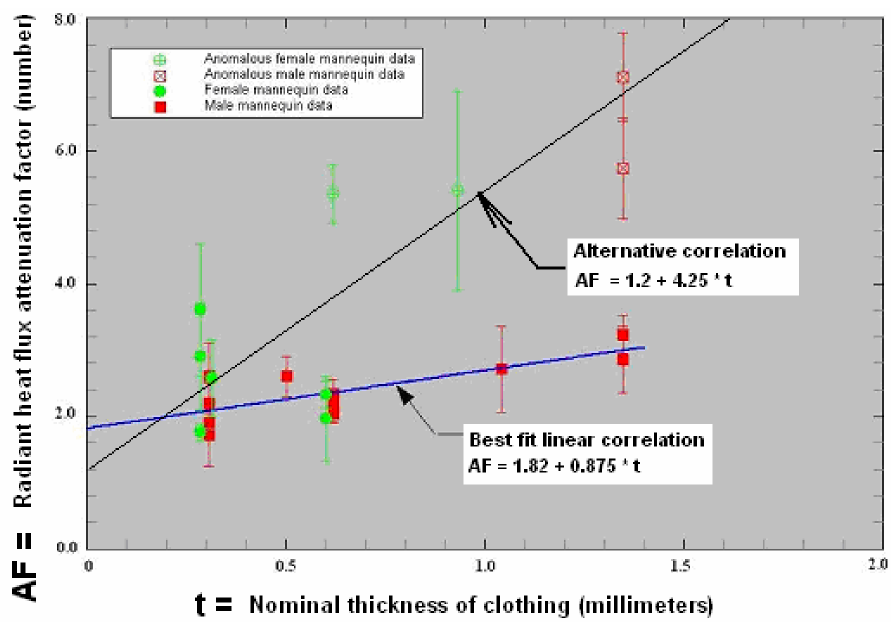

Figure E-5: Radiant heat flux attenuation factor vs. clothing thickness

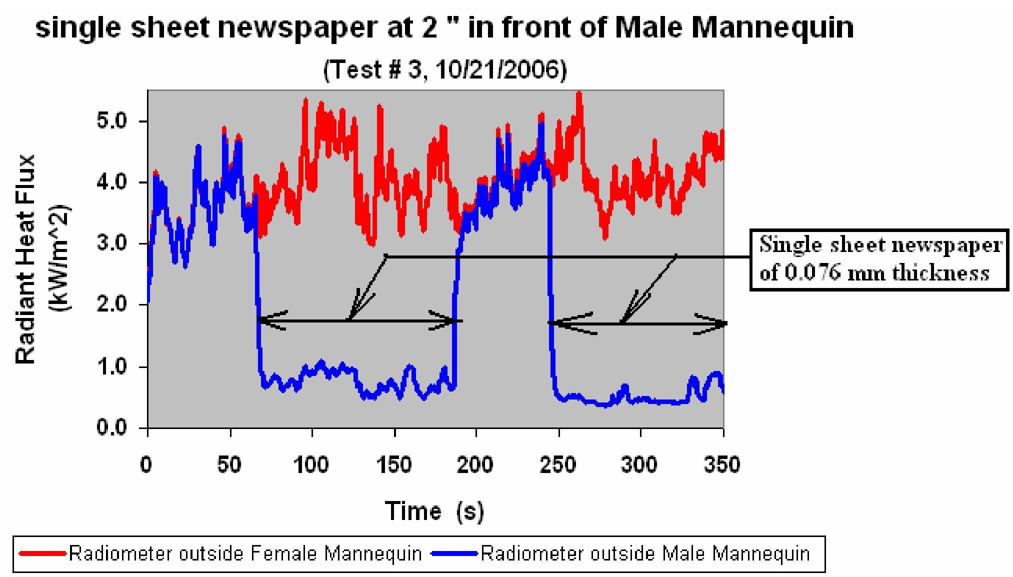

Figure E-6: Attenuation of radiant heat flux by a single sheet of newspaper

It is also noticed in these tests that the attenuation factor of the newspaper depended upon the magnitude of the exposure radiant heat flux. The exact cause of this is not fully understood. It may due to the drying of the paper due to heat exposure and hence higher "transmissivity" (or lower attenuation factor) values. The data from all newspaper obstruction tests are summarized in Figure E-7. As can be seen from this figure the attenuation factor by a single sheet of newspaper is much larger than that from the clothing immediately on top of the skin.

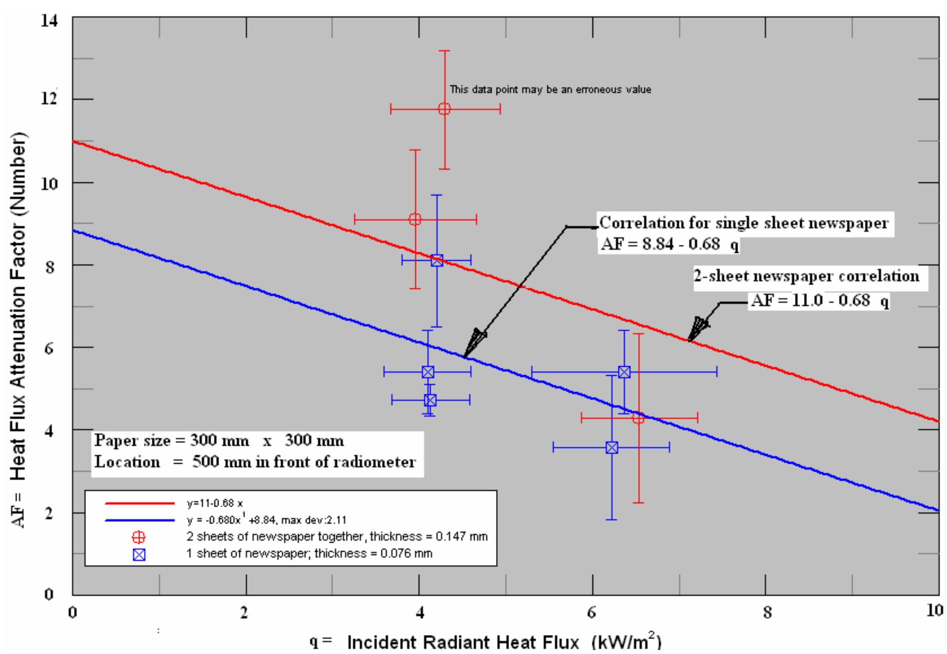

Figure E-7: Radiant heat attenuation factor vs. newspaper sheet thickness

Human exposure trial results

In the trials in which only the handheld radiometer was used to record the magnitude of the heat flux incident upon the author no records are available on the time wise variation of the heat flux to which the author was exposed. The information from the display screen (similar to the ones on hand calculators) was recorded on paper after the tests. Because of this there is some uncertainty in the "best estimate" of the mean and the range of heat fluxes to which the author was exposed. The duration of exposure of the author could however be obtained from the video films of the tests. Table E-1 shows the results of "after-the-fact record" of heat fluxes to which the author was exposed in several tests. As can be seen, the heat flux levels do vary from a low of 2.2 kW/m^2 to a high of 5 kW/m^2 (with bursts that exceeded this value by at least 1 to 1.5 kW/m^2). The reason for terminating the experiment at the indicated durations for low level heat fluxes was due to the wind shift which started blowing the fire plume towards the author an not because of his inability to withstand the levels for a longer duration.

In the subsequent tests the author wore the radiometers that had been fixed to the mannequins. These radiometers recorded the data in 0.1 s intervals. Figure E-8 is from one such tests. Clearly it is seen from this figure that the author was exposed to a mean heat flux of 4 kW/m^2 for over 45 s with absolutely no burns, pains or skin blisters on the parts of his body not covered by clothing. He did not feel any heat sensation more intense than what may be felt in front of a hot fireplace in a home.

Table E-1: Handheld radiometer data on human exposure to radiant heat

Test Date in 2006	Expo-sure session #	Mean flame height [m]	Location of human subject(1) [m]	Mean radiant heat flux and [range] [kW/m^2]	Exposure duration(2) [s]
09/28	1	5.1	12	2.2 [2.1 - 2.9]	53
	2	4.2	8	4.4 [3.8 - 5.8]	17
	3	5.1	10.5	2.2 [2.7 - 5.8]	60
	4	5.9	11.0	2.2 [2.0 - 3.0]	103
	5	5.5	7.9	4.4 [3.8 - 6.0]	22
	6	4.3	7	4.4 [3.8 - 5.8]	21
	7	5.5	7.9	2.2 [2.0 - 3.2]	120
10/05	1A	7.2	9.3	5.0 [4.9 - 6.2]	26
	1B	7.1	12.2	5.03 [4.0 – 8.0](3)	93
	2	6.6	11.1	5.0 [4.5 - 6.0]	42
	3	5.5	8.7	5.0 [4.9 - 6.2]	24
11/02	1	6.7	9.7	5.0 [4.9 - 6.2]	57
	2	5.0	9.3	5.0 [4.9 - 6.2]	16
	3	5.1	8.4	5.0 [4.9 - 6.2]	32
	4	5.0	8.8	5.0 [4.9 - 6.2]	20
	5	4.7	9.1	5.0 [4.9 - 6.2]	31

Notes: (1) All distances are from the center of dike
(2) The author did not suffer any injury over the duration indicated in the table
(3) Based on the outside radiometer on one of the mannequins next to the author

In all of the exposure tests, the author experienced heat flux levels close to 5 kW/m^2 for durations of time in tens of seconds. In many instances the incident heat flux levels were much higher (the highest experienced, albeit for very short durations of time of the order of 5 seconds, was 7 kW/m^2). In one test he was able to stay at one location and experience a mean heat flux level of 3.9 kW/m2 for over 100 seconds with occasional bursts of heat flux above 5 kW/m^2 and 6 kW/m^2.

Temperature data

The mannequin "skin" temperatures rose considerably from the ambient values for even short durations of exposure. This is as expected since the mannequins, made out of fiberglass, do not conduct and there in no other cooling mechanism. Hence the "skin" temperature rises quite rapidly. This is in contrast to the experience of the author exposed to the same levels of heat flux and for the same durations of time. Figure E-9 shows a typical comparative result indicating the 'normal body temperature" being maintained by the human being where as the mannequin skin temperature rising to almost 60 ^{o}C. It is argued that in the case of a human being the increased blood circulation and the sweating (which indeed was experienced by the author) keeps the skin temperature steady where such mechanisms are absent in a "dummy."

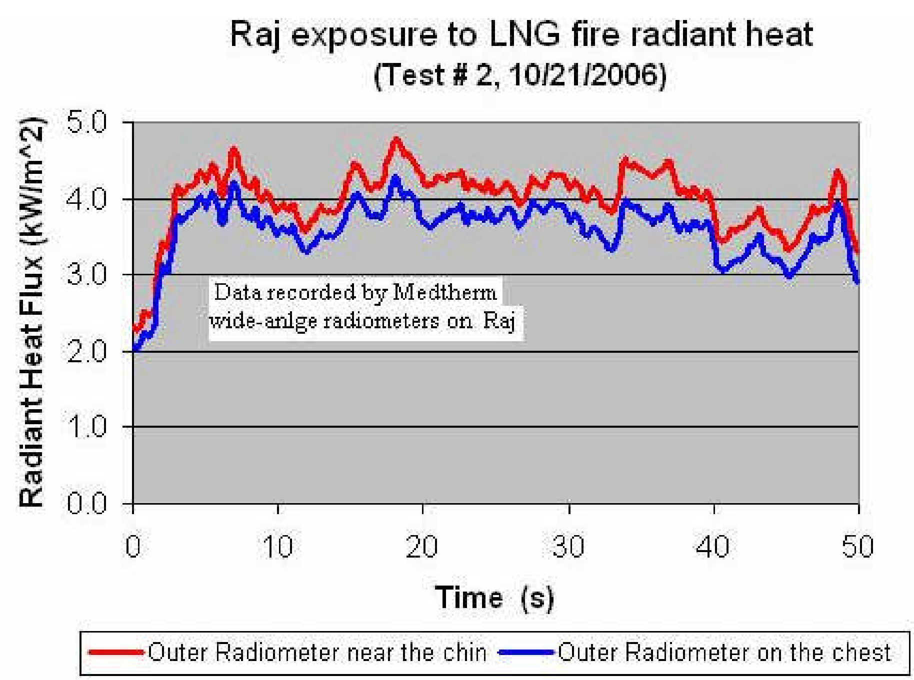

Figure E-8: Human exposure to a LNG fire radiant heat flux- test 2 of 10/21

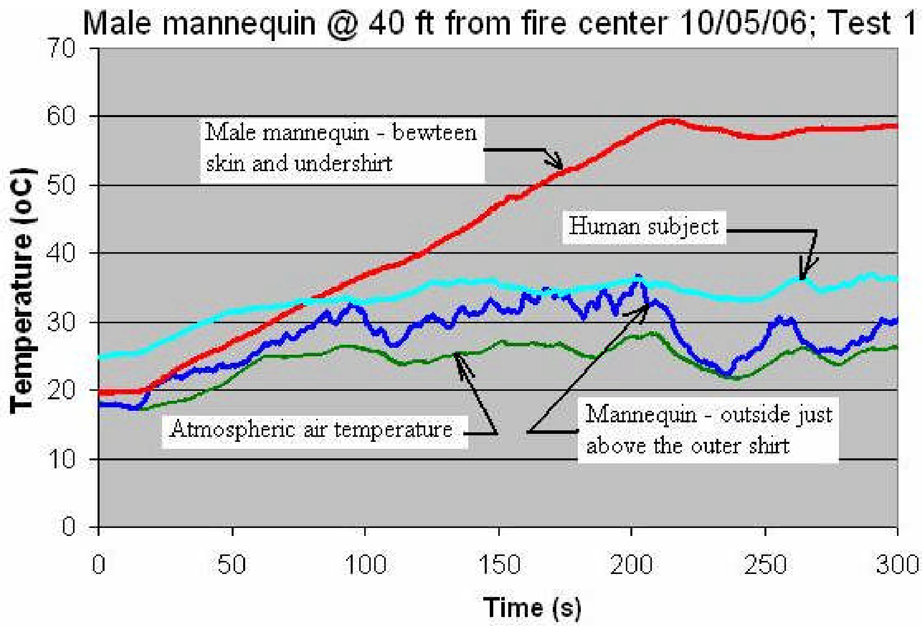

Figure E-9: Comparison of mannequin and human skin temperatures under identical fire exposure conditions

Reproducibility of data & Measurement Errors

The calibration of the radiometer and that of the thermocouples are accurate to less than 1% error. Therefore, the values recorded for the heat flux and temperature are accurate within 1% of the actual value of the heat flux incident at the location of the instrument or the temperature to which the thermocouple is exposed. The temporal variability seen in the measured values (of heat flux or temperature) at the location of the mannequins or at the location of the human subject are therefore only due to the variability of the heat flux incident on the instrument due to variability in the fire plume tilt, size and changes in fire emission caused by the wind (both wind speed and wind direction) and turbulence in the fire. When the wind is blowing from the mannequins to the fire, the fire plume tilts away from the mannequins, causing a lower level of heat flux to be incident on the mannequins. A higher heat flux is recorded when the fire plume tilts towards the mannequins. In effect, the wind and combustion induced turbulence determines the variability (about a mean) value of the heat flux measured at any specific distance from the fire. Hence, the mean value of heat flux may be reproduced (to within 1% accuracy) at any specified distance from the fire provided all other parameters such as the fire size, wind speed, LNG burning rate, etc remain constant.

E.5 Findings

The following principal findings result from the review and evaluation of the data collected in this series of field tests.

Finding # 1: Ordinary civilian clothing, even a single layer clothing, provides a factor of at least 2 reduction in the magnitude of radiant heat flux reaching a person's skin for relatively long term exposures (of the order of minutes) at an exposure level of 5kW/m^2 or close to it.

Finding # 2: Any object that intervenes between the heat flux source and the object receiving the heat flux results in a substantial decrease in the heat flux to the object. The object could be as thin as a single sheet of newspaper.

Finding # 3: At 4 kW/m^2 radiant heat flux level a person can be exposed for as long as 60 to 120 seconds without feeling either severe pain or suffering any skin burns. At 5 kW/m^2 a person's exposed skin can withstand the heat flux for at least 25 to 30 s, without much pain, permanent injury or skin burns.

Finding # 4: The temperature measured on the skin of a fiberglass mannequin exposed to radiant heat does not provide a representation of the temperature attained by the skin of living human being.

The above findings are very conservative in that the durations of tolerance of a given magnitude heat flux without any pain or injury are in many tests longer than indicated above. Similarly, the attenuation factors of clothing and of intervening objects have also been recorded higher than indicated in the findings.

E.6 Conclusions and Recommendations

Based on the results and the findings the following conclusions are made from the experiments conducted in this series.

E.6.1 Conclusions

1 The current criterion for public safety in the US regulations and standards (5 kW/m^2 for 30 s exposure) is very conservative and represents a very high level of factor of safety. This is because while the criterion is based on exposure of bare skin, as is seen from the results of this investigation, even thin clothing on the skin provides a reduction of heat flux (to the skin) by a factor of 2 to 3. Hence, when the outside the clothing heat flux level is, say, 5 kW/m^2, the skin will feel only about 1.67 kW/m^2 to 2.5 kW/m^2.

2 Very simple and even single layer clothing and other simple objects provide significant reduction in radiant heat flux to the skin of a person. The reduction in the heat flux levels by single layer of clothing can amount to a factor of 2 or 3. Newspaper sheets in front of the face or hands can reduce the heat flux levels by factors of 5 or more.

3 Mannequins can be used as a substitute for live human tests to determine the effectiveness of clothing to reduce radiant heat flux to the skin. However, mannequins cannot act as a substitute when determining the skin temperature rise due to exposure to a radiant heat flux, because the human physiology of skin cooling is completely and drastically different from that in a mannequin. A mannequin skin, generally constructed of fiberglass, does not conduct heat. Also in a mannequin there is no mechanism of heat removal by internal cooling or sweating as in the case of a human being.

4 Because of the reduced area of the skin exposed to the fire in a clothed person, the human physiological systems may work to reduce the effect of the heat flux on the exposed part of the skin by carrying away heat and initiating other protective mechanisms, such as sweating. That is, a partially clothed human body may withstand a higher heat flux exposure than a completely naked body.

E.6.2 Recommendations

In the tests conducted not all parameters that could have been varied were actually varied or when varied the range of variation was limited. Some of the parameters will have significant influence on the results and need to be used in future tests. With this in mind the following recommendations are made for future research.

1 Tests should be conducted with mannequins protected from fire during the periods when no data are recorded. This will ensure that conditions that prevail in a sudden and unexpected exposure of a person to LNG fire (in an accident scenario) can be duplicated properly.

2 Human subject, if used, must be able to “cool off” or completely protected from fire exposure (however small) before initiating additional data gathering trials.

3 Tests with hand held radiometer or strapped on radiometer must be designed such that the instruments are capable of relaying the data captured by wireless to the computer at rates exceeding 10 Hz. Wiring limits the ability of the person to ambulate to maintain the same heat flux level. Wiring also limits the ability to move the mannequins quickly.

4 Future tests should be designed to move the mannequins easily (located on wheeled trolleys) so that their location with respect to the fire can be changed quickly and easily.

5 Experiments similar to the ones conducted in this series need to be carried out with bigger LNG fires for the following reasons. In a larger LNG fire,

- The distribution of radiant energy as a function of the spectral wavelength will be different compared to that in a smaller fire due to soot effects in larger fires.

- The distance to 5 kW/m^2 heat flux location will be larger. Because of the larger distance, the absorption of the IR in the atmospheric water vapor and CO_2 bands will be higher and could be significant. This may influence the ability of a person to withstand an overall heat flux of 5 kW/m^2 for longer duration because the spectrum of energy incident on the skin will be devoid of energy in the water vapor and CO_2 bands.

- A given wind speed has smaller effect on larger fires than on smaller diameter fires. Therefore in a larger fire, a given wind speed will produce less variations in fire plume tilt and, consequently, more steady incident heat flux.

Chapter 1

Introduction

1.1 Background

The US Code of Federal Regulations, 49 CFR, Part 193.2057 refers to 'Thermal radiation protection' from potential LNG fires in a LNG facility and states: *"Each LNG container and LNG transfer system must have a thermal exclusion zone in accordance with section 2.2.3.2 of NFPA 59A* (2001) edition." The determination of the exclusion zone distances, in NFPA 59A (section 2.2.3.2), for people exposure, is based on using one of the following hazard criteria:

Table 1-1
Radiant heat exposure criteria in NFPA 59A

Locations	Magnitude of the maximum radiant heat flux at the specified location	
	(kW/m^2)	(Btu/ft^2 hr)
At a property line that can be built upon for ignition of a design spill as specified in § 2.2.3.5	5.0	1,600
At the nearest point located outside the owner's property line that, at the time of plant siting, is used for outdoor assembly by groups of 50 or more persons for a fire over an impounding area containing a volume of LNG determined in accordance with § 2.2.2.1	5.0	1,600
At the nearest point of the building or structure outside the owner's property line that is in existence at the time of plant siting and used for occupancies classified by NPA 101 '*Lire Safety Code*", as assembly, educational, health care, detention and correction or residential for a fire over an impounding area containing a volume of LNG determined in accordance with § 2.2.2.1	9.0	3,000

There has been considerable misinterpretation in the application of the above criteria in LNG plant hazard assessment. In most hazard assessment calculations the 5 kW/m^2 criterion is used for determining the exclusion distance for people exposure hazard. However, this may not be entirely appropriate. This is because the NFPA's intent is to apply this radiant exposure criterion only when calculating the distance to open areas where there is a likelihood of 50 or more persons congregating at any one time. Unfortunately, the same criterion is used for exclusion distance calculations even when there are less than 50 in an open area. Furthermore, this criterion is also used to determine the hazard distance to residences (where people are within a building for a very large part of the day). In fact, the NFPA 59A criterion that will be applicable to residences and other covered buildings is the 9 kW/m^2 and not 5 kW/m^2. Also, the same misapplication of the criteria occurs when used for calculating the hazard distance from (LNG) pool fires caused by potential spill scenarios from ships.

Other important issues not addressed either by 49CFR, Part 193 or NFPA 59A are the duration of exposure and the mitigating effects of passive parameters such as the shadow cast by an object, high-rise buildings, trees, residences, or other obstructions, and the radiant heat attenuation by civilian clothing worn by people during their daily activities. It is known that infrared (IR) radiant heat from a fire is felt only when there is a line of unobstructed sight between the radiator (fire) and the receiver (person or object exposed). Any intervening object effectively reduces or eliminates the effect of IR. One important fact that should be considered is that all persons are clothed and, hence, the extent of injury that may be caused by exposure to radiant heat will be reduced or eliminated depending upon the area of the body that is protected by clothing (summer or winter attires), type, material and thickness of clothing, and the duration of exposure.

1.2 Literature review

1.2.1 Burn injury hazard criteria

The 1979 edition of NFPA 59A stipulated (for the first time in the NFPA LNG Standard) the hazard criterion for public exposure with a level of 5 kW/m^2 (1600 Btu/ft^2 hr). Table 1-2 shows the language that appears in the 1979 edition of NFPA 59A and the substantiation provided for introducing the criterion for people exposure. The substantiation does not provide the scientific basis on which the magnitude of the thermal exposure flux (5 kW/m^2) was stipulated.

1.2.2 Skin burn injury experiments

The implicit assumption in the development of the hazard exposure criteria indicated in Table 1-1 is that a person may experience a reversible 2^{nd} degree burn on the exposed portions of the body if the exposure is longer than 30 seconds. This is based on the information in the medical literature on human exposure tests, in the 1940s, in which a very small area (about 2 to 3 mm in diameter) of the forearm skins of volunteers were exposed to different magnitudes of radiant heat fluxes [Buttner, 1951]. Animals (specifically pigs) have also been used to determine the extent of skin injury when exposed to different levels and durations of thermal radiation. Raj [1977] has presented a review of the literature (available at that time) on skin burns and the criteria for burn injury. More recently, Hockey & Rew [1996], and Sullivan and Jagger [2004] have reviewed the literature on skin burns with a view to using the information in pool fire hazard modeling. These data indicate that there are different approaches to specifying the criterion for burn injury to a human skin exposed to radiant heat.

It is known from the medical literature that a 2^{nd} degree burn occurs when the surface temperature of the skin attains 55 ^oC, from its normal 37 ^oC, [Mehta, et al, 1973], and subsequently the skin absorbs another 2 cal/cm^2 (83.7 kJ/m^2) energy. Hendler, et al [1958], report tests conducted to determine the thermal properties of human skin exposed to radiant heat. The average value of the thermal property ($K\rho C$) for human skin is indicated as $[18.92 \pm 1.4] \times 10^5\ W^2\ s/m^4\ K^2$. Stoll & Greene [1959] report tests in which the blackened forearms of human subjects were exposed to radiant heat flux values ranging from 2 kW/m^2 to 16.7 kW/m^2. Pain sensations are reported to have been felt only when the receptors in the skin at a depth of 200 μm (0.2 mm) were elevated to a temperature of 43.2 ^oC. In addition, there are other medical literature on the exposure of human skin and tissue (especially ocular tissue) to the harmful effects of exposure to intense IR radiation. These experiments were conducted in the laboratory with the subject skin surface (fore arm) very close (of the order of a few centimeters) to the heat source, which was a tungsten lamp, radiating very much like a black body. Experiments conducted by Hardy [1956] in the 1950s with human skin exposed to different wavelengths of light in the visible and near infrared indicated that (i) about 20% of the incident energy in the 0.5 to 1.5 μm wavelength range gets reflected off the skin, and (ii) in the spectral wavelength range 1 to 2.4 μm the skin appears to be almost non-absorbing except for the water vapor band absorption.

While a considerable body of literature seems to exist in medical journals on skin injury by exposure to heat radiation from fires, these are misleading to the extent there have been no direct measurement of skin injury or burns arising from the exposure of a human being at some distance from a real, large size LNG or any other type of fire. All data that exist are based on small, laboratory-scale tests, extrapolations from direct flame contact injuries and theoretical modeling. Without minimizing the importance of the results that have been collected over the past 6 decades, suffice it to say that there have been no documented evidence of any person being injured, let alone being killed by exposure to any large fire radiant heat at a distance. As is discussed below, other important phenomena associated with large fires occur, which have a bearing on the potential for burn injury and the level of radiant heat flux at which these injuries can occur.

1.2.3 Radiant heat energy spectrum from a LNG fire and skin burns

The spectrum of radiant heat received by an object at a distance from a large LNG fire may not be represented completely as that from a black body emitter. This is because of the absorption of radiant energy in selective bands by the atmospheric water vapor, carbon dioxide and other molecules. Also, in large fires the black smoke formed due to incomplete combustion of the fuel forms a shroud around the emitting surfaces of the fire thereby absorbing considerable quantity of the emitted thermal radiation. The carbon and hydrogen (C & H) radicals in the smoke also absorb selectively in bands in addition to the scattering of radiation by the smoke particles. Hence, the spectrum of radiant energy incident on a subject at some distance from a large hydrocarbon fire, such as an LNG fire, is considerably different from that of a black body spectrum. Even for relatively short distances of a few tens of a meter, the incident energy spectrum seems to be devoid of the radiant energy in the water vapor bands and show considerable absorption in the CO_2 bands [Malvos & Raj, 2006]. The peak energy in the spectrum occurs at about 1.94 μm for a LNG fire radiation, which is very close to water vapor absorption band center wavelength.

The above results are very interesting when applied to the radiant heat from a LNG fire incident on a skin at a significant distance from the fire. The incident fire spectrum is devoid of energy in the water vapor bands and therefore there is no energy in the incident beam that can be absorbed by the water in the skin, whereas a considerable energy in the 0.5 to 1.5 μm wavelength range is reflected and the rest of the incident energy is transmitted directly through the skin to the blood without absorption. The upshot of these phenomena will be to significantly reduce the temperature increase of the skin material and, hence, reduce the potential for skin burn even when exposed to durations of 30 seconds or longer.

Table 1-2
First-time Introduction of Thermal Radiation Hazard Criterion in NFPA 59A Standard

59A-8 (2120)
SUBMITTER: Liquefied Natural Gas Committee
RECOMMENDATION: 2120. Amend extensively as follows:
2120.

(a) Provision shall be made to prevent a radiation flux that could result from ignition of a design spill defined in 2121 from exceeding 5000 W/m^2 (1600 $Btu/Hr/Ft^2$) at a property line which can be built upon when atmospheric conditions are zero wind speed, 21C (70 F) temperature and 50 percent relative humidity. This provision may be complied with by a separation distance determined by Formula 1A.

FORMULA 1A

$$d_1 = 3\sqrt{A_1}$$

where,
d_1 = distance, in meters (feet), from the nearest edge of the applicable design spill to a property line which can be built upon, and
A_1 = Surface area, in square meters (square feet) of LNG, resulting from the applicable design spill.

(b) Provision shall be made to prevent a radiation flux from a fire over an LNG impounding area from exceeding 5000 W/m^2 (1600 $Btu/Hr/Ft^2$) at the nearest point of a place which at the time of plant siting is used for outdoor assembly by groups of 50 or more persons when atmospheric conditions are zero wind speed, 21 C (70 F) temperature and 50 percent relative humidity. This provision may be complied with by a separation distance determined by Formula 1B.

FORMULA 1B

$$d_2 = 3\sqrt{A_2}$$

where,
d_2 = distance, in meters (feet), from the edge of impounded LNG to the nearest point of the place of assembly, and
A_2 = surface area, in square meters (square feet), of impounding area is filled with a volume, V, determined in accordance with 2110.

(c) Provision shall be made to prevent a radiation flux from a fire over an impounding area from exceeding 9000 W/m^2 (3000 $Btu/Hr/Ft^2$) at the nearest point of a building or structure in existence at the time of plant siting and used for purposes classified by NFPA 101, Life Safety Code,* 1976, as Assembly, Educational, Health Care, Penal or Residential when atmospheric conditions are zero wind speed, 21C (70 F) temperature, and 50 percent relative humidity. This provision may be complied with by a separation distance determined by Formula 1C.

FORMULA 1C

$$d_3 = 2\sqrt{A_3}$$

where,
d_3 = distance, in meters (feet), from the edge of impounded LNG to the nearest point of the building or structure, and

A_3 = surface area, in square meters (square feet), of impounded LNG when the impounding area is filled with a volume, V, determined in accordance with 2110.

(d) Existing 2120 amended by replacing "10,000 $Btu/Hr/Ft^2$" and "70° F" with "30,000 W/m^2 (10,000 $Btu/Hr/Ft^2$)" and "21 C (70 F)"; by changing "Formula 1" to "Formula 1D" in the text and caption for the formula; and changing "d" to "d_4" and "A" to "A_4" in the formula itself and its legend.

SUBSTANTIATION: The Committee is of the opinion that a high degree of public safety is achieved by compliance with the present provisions of 2120, particularly upon consideration of two factors of major importance, viz., (1) the probability of occurrence of an event which could lead to a fire over the total impounding area, and (2) the time delay expected between the event and the buildup of maximum radiation flux. Nevertheless, the Committee desires to increase the degree of public safety by additional provisions.
Proposed 2120(a) recognizes certain sized accidental spills as credible (see 2121 for "design spill" definition in the 1975 edition of 59A and proposed 2122), and limits the allowable radiation at the property line from such spills to a level below that considered hazardous to life.
Proposed 2120(b) and (c) give special consideration to the type(s) of activity or use of the area adjacent to the plant. It is recognized that persons in an outdoor open area would intercept a greater level of fire radiation than would be the case for persons inside buildings or structures where enclosure in structural components would intercept the radiation. Therefore, a limit is set for outdoor exposure at places of moderately large group assembly below the level considered hazardous to life. Further, a limit is set for exposure to those buildings and structures wherein the occupants might not be alert and able to physically act to establish their own self preservation in the event of an emergency. This limit is set below that which would cause the building or structure to cease to provide shielding of the radiation.
Formulas for separation distances are given which may be used to comply with the provisions. However, use of the formulas is not mandatory and the option exists for either determination of separation distances by calculation or to employ fire radiation control methods other than separation distance alone, provided that all provisions of 2120 are met.

Source: "Technical Committee Reports, 1979 Fall Meeting, Nov 12-14, 1979, Phoenix, AZ. National Fire Protection Association, Boston, MA 02210.

It is uncertain what fraction of the body has to be exposed to a radiant heat from a fire (with the incident energy spectrum devoid of water vapor band energy) before a serious injury to a person could result in 30 seconds. Secondly, if the protection provided by clothing increases the time of exposure by a significant duration beyond which burn injuries occur, then the response action by emergency services or self initiated shelter seeking response by individuals could provide sufficient protection against thermal injuries. Unfortunately, there do not seem be full-scale test data of the protection provided by clothing when exposed to radiant heat from a large fire. The information on clothing protection available in the literature is indicated below.

1.2.4 Effect of clothing on skin burn injury protection

Clothing normally worn by people can partly absorb, partly reflect and scatter incident thermal radiation and thus protect the covered skin from experiencing the full intensity of the incident radiation. Stoll and Chianta [1970] show that the time to produce "white" burns in rats, with a 4 mm air gap between a fabric and the skin increased by a factor of 3 compared to the time to produce the same burn without the fabric. For large radiant heat flux levels (30 kW/m^2, which levels would be experienced when the person or an object is very close to a fire) the researchers found that the absolute protection time provided by normal clothing (of 1 to 1.5 mm thickness) was short and that much thicker (and multi layered) clothing, such as is worn during winter months, was necessary to provide any burn protection. Theoretical work by Haskestad, et al. [1971] shows that the thermal protection offered by the apparel depends upon the gap between skin and the clothing, in addition to the thermal properties of the cloth itself. In these calculations high heat flux levels (33.5 kW/m^2) were used. No results are presented for low thermal flux levels of interest (5 kW/m^2) to this study. If the results are extrapolated to 5 kW/m^2 intensity level, the duration for charring of the cloth is found to be longer than 300 seconds. The source characteristics used in these assessments were that of a black body.

From the above brief discussions on the characteristics of LNG fires, the spectrum of incident radiation, effect of clothing, etc., it is seen that, unfortunately, no systematic evaluation of each of these effects (individually and in combination) have been conducted with field experiments with LNG fires or other hydrocarbon fires. Therefore, it is uncertain at present whether the 5 kW/m^2 criterion in the NFPA 59A Standard and in 49 CFR Regulations is too conservative a value for determining the (hazard) distance to potential skin burn hazard to people from large LNG fires. It is further noted that the occurrence of a large LNG fire in any specified LNG facility has an extremely low probability of realization. Also lacking are field test data indicating the effectiveness of ordinary clothing that people wear during their normal activities and the degree of protection that the clothing provides. It is with a view to developing such important data that the tests indicated in this report were conducted.

1.3 Project Objectives

The objectives of the research indicated in this report were to determine:

1 The effectiveness of ordinary civilian clothing, both single layer and multi layer, in attenuating the radiant heat flux from a LNG fire, at a level of 5 kW/m^2 (1600 Btu/hr ft^2) .

That is, to determine the fraction of the heat flux incident on the clothing that actually reaches the persons skin covered by the clothing.

2 The reduction in the heat flux reaching the person when shaded by simple objects such as a thin newspaper sheet held in front.

3 The level of heat flux that a human being dressed in normal civilian clothes can withstand without significant pain or suffering skin burn injury and the duration over which such heat fluxes can be withstood.

Although the 3rd objective was not part of the original design of the tests, the project manager (and author of this report) utilized the opportunity to volunteer and test the adequacy and validity of current correlations in the medical and LNG hazards assessment literature on the degree of tolerability of radiant heat fluxes and the duration of safe exposure without suffering skin burns.

The experiments conducted to fulfill the above objectives are described in the following chapters. Chapter 2 provides the details of the tests facility, the equipment and instruments used, instrument calibration results, and details of the clothing and mannequins used in the tests. In Chapter 3 are indicated the types and number of tests conducted, data gathered, analyses of the results gathered and the principal findings. Chapter 4 includes the conclusions and recommendations from the study.

Chapter 2

Description of Equipment and Tests

2.1 Test facility

A series of tests involving the ignition of a pool of LNG in a dike during its steady state evaporation was conducted at the test and firemen training facility of the Department of Fire Services (DFS), Commonwealth of Massachusetts in Stow, MA. These tests were performed in conjunction with the training of firemen from Everett, MA to respond and manage a LNG pool fire on land. The opportunity presented by the live LNG fire training of firemen was utilized to obtain important data on the effects of radiant heat from a field size LNG pool fire.

The DFS facility consists of several buildings for administrative and classrooms, and also a field test and training area encompassing about 10 acres. A part of the training ground surface (200,000 sq.ft. area) is paved. Also, the training facility has a number of fire test buildings, equipment, water drafting pit and other resources suitable for conducting fire experiments. Figure 2-1 shows one view of the test facility including the LNG fire test dike and the observation tower. Figure 2-2 shows, schematically, a plan view of the test facility including the observation tower location and the location of the test dike in relation to the observation tower and the LNG storage tank. Figure 2-3 shows the details of the concrete floor, sand wall dike. Figure 2-4 shows the depth gauge showing the depth of the dike floor from the end section of the fill pipe.

The LNG fires were conducted in an approximate square dike of top dimensions 10.5 ft x 10.5 ft and bottom dimensions 8 ft x 8 ft, built over a concrete surface. Figure 1 shows a schematic view of the test dike. The walls of the dike were made of wet sand and sloped both into the dike and outside the dike.

LNG stored in a tank about 1000 ft away from the dike was pumped under the tank pressure and spilled into the dike through the spill pipe shown in Figure 2-5. About 500 gallons of LNG was spilled into the dike over a period of about 10 minutes. Part of the spilled liquid was allowed to boil from the heat transfer from the dike floor and the liquid wetted walls. The moisture in the sandy walls of the dike would freeze forming a self-sustaining, impervious, refractory dike wall. The vapors produced by liquid boiling were dispersed using two fire-hose streams directed at the vapors outside the dike. Ignition of the pool was initiated only after the liquid boiling was reduced to such a level that one could actually go near the dike and see the liquid pool inside the dike. The depth of LNG in the dike at the time of quiescent boiling (steady state evaporation due to atmospheric convective heat leak), and just before ignition, ranged from 10 inches to 13 inches. At a liquid depth of 13 inches the horizontal dimensions of the liquid surface was calculated to be 10 ft x 10 ft. After each fire test, parts of the dike wall that spalled due to heat were re-built with wet sand.

Figure 2-1: View of the dike, the LNG fill-pipe and the observation tower

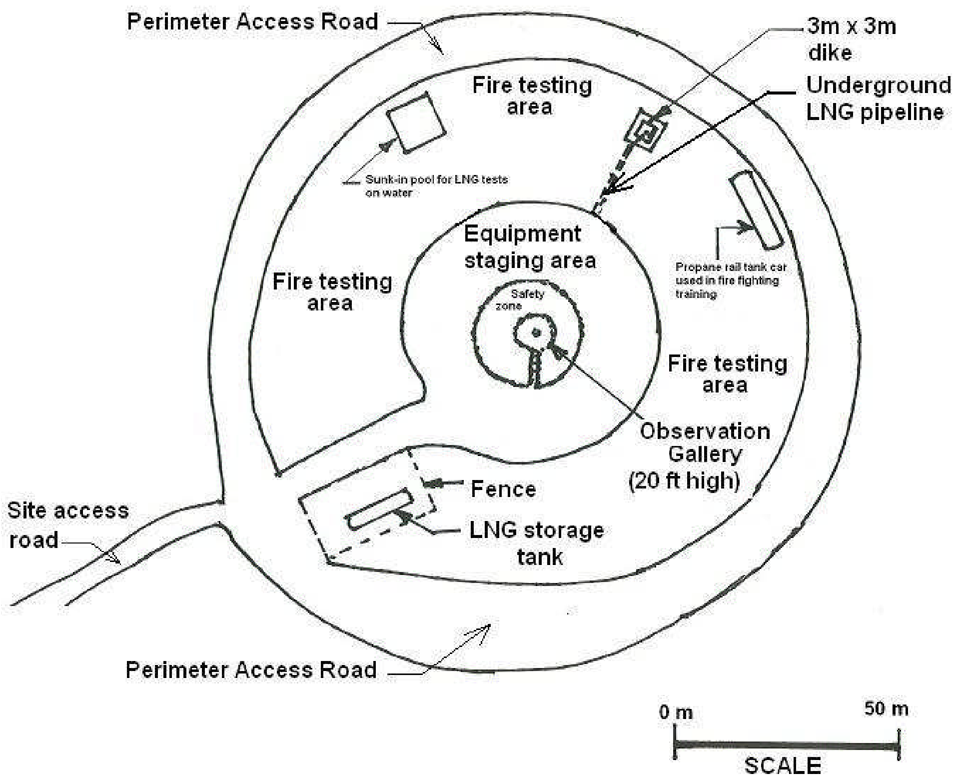

Figure 2-2: Schematic diagram of the test site plan view, location of observation gallery and LNG fire dike

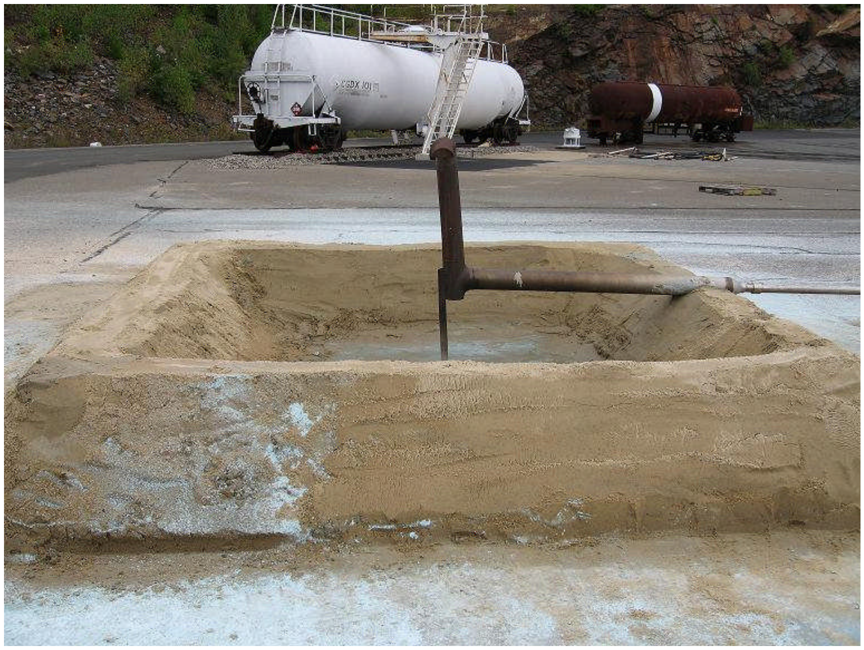

Figure 2-3: Close-in view of the 10 ft x 10 ft (top) dike with concrete-floor and sand-walls

Figure 2-4: Dike depth illustrated with a ruler

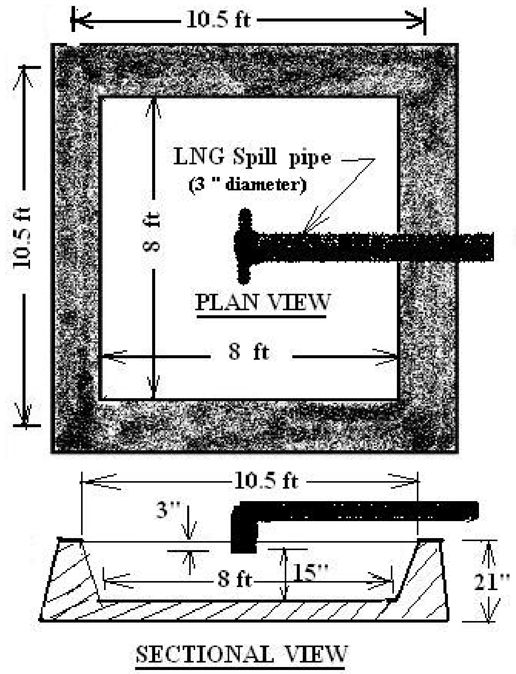

Figure 2-5: Schematic diagram of the dike with dimensions

2.2 Parameters measured in the tests

A number of parameters were measured in the tests. The instruments used for gathering these data are described in section 2.3. The measured parameters included (i) the local meteorological conditions (temperature, wind speed and direction, and relative humidity), (ii) the incident radiative heat flux and its temporal variation at the location of mannequins (measurements both outside the clothing and inside the clothing), and (iii) the closest distance to the fire reached by a person and duration of exposure at about a radiant heat flux level of 5 kW/m^2.

2.3 Materials, instruments and other equipment used

2.3.1 Mannequins:

In order to assess the effectiveness of ordinary clothing in attenuating the radiant heat flux to a person exposed to about 5 kW/m^2 heat flux level, two mannequins were used in each of the tests. The mannequins were made of fiberglass and represented the average size of a person. Figure 2-6 shows the male and female mannequins used in the tests. The mannequins are made of fiberglass and are supported on a glass pedestal with a single vertical stem inserted into a hole cut out at the back of the leg.

The mannequins were used in the tests without arms (to facilitate the ease of clothing them in the field) and clothed both on the chest (shirts) and on the legs (pants). Tests were conducted with single layer clothing and double layer clothing. Additional details of the tests are indicated in Chapter 3.

Figure 2-6: Picture of the fiberglass mannequins used in the field experiments

2.3.2 Clothing used in the tests

The clothing for the mannequins were purchased from a department store and represented the normal civilian clothing worn by men and women during most of spring or summer. The selection was at random and did not represent any particular brand of clothing or fabric material. The male clothing purchased consisted of a pair of full sleeve outer shirts (one white and the other black) and a white cotton undershirt and light brown pants. The female clothing consisted of somewhat tighter clothing including a green inner shirt (half sleeve) and a red outer (full sleeve) shirt and appropriate pants. The outer shirt was found to fit the female mannequin tightly so that the outer and inner shirts would be very close compared to that in the male clothing. Other details of the clothing used in the tests including the fabric thickness are indicated in Table 2-2.

In each of the tests the principal investigator of the project (Dr. Raj) approached the LNG fire wearing normal civilian clothing to determine the radiant heat flux level he could withstand (and the duration of exposure) without suffering any burns or permanent skin damage. The details of the clothing worn by this investigator are also indicated in Table 2-1.

In a few tests single sheet of a newspaper and double sheets of a newspaper were used to determine the effect of thin sheets of paper on the attenuation of radiant heat flux. Single sheet of newspaper used had a thickness of 0.076 mm (3×10^{-3} in) and double sheets total thickness (as squeezed by the micrometer) was 0.147 mm (5.8×10^{-3} in).

2.3.3 Wide-angle Radiometers:

Two types of wide-angle radiometers were used in the tests. These included (i) Medtherm infrared radiometer [model 32R (ZnSe)-1-0-394-21325A], and (ii) Medtherm heat flux transducer [Model # 32F-1-394-21037]. The detailed dimensions, specifications and calibrations of these radiometers are indicated in Appendix A. One radiometer was located just under the chin of the mannequin and the other 5 cm (2 inch) below.

Two radiometers (see description of the radiometers in the next section) were placed on each of the mannequins, one essentially on the chest and the other slightly below the chin. The radiometer under the chin was the MedTherm infrared radiometer (model 21325A). The one on the chest was the MedTherm heat flux transducer (model # 21037). Both radiometers were attached to a vertical aluminum bracket which itself was attached by bolts to the body of the mannequins. The locations of the radiometers on the mannequins are shown in Figure 2-7A and Figure 2-7B, respectively for the male and female mannequin.

The radiometer under the chin was placed as to protrude outside the clothing, by about 5 cm (2 inches). The radiometer on the chest was essentially flush with the bracket surface, which itself was about 1 cm (≈½ inch) from the "skin" surface of the mannequins. In addition, the chest radiometer was covered by clothing in front of it and therefore would receive and measure only the radiant heat flux that penetrated through the clothing. The vertical distance between the two radiometers was 5 cm (2 inches). The locations of the radiometers vertically above the local ground are indicated in Table 2-2.

Table 2-1: Details of the clothing used in the tests (on mannequins and human subject)

Exposed subject	Garment color	Garment fabric	Garment location	Thickness of garment (mm)
Male Mannequin	White undershirt	Cotton	Inner	0.320 & 0.292 Mean = 0.306
	"US Polo" White full sleeve shirt	Cotton	Outer	Mean thickness over button flap = 1.041 Mean thickness in other areas = 0.313
	Black, full sleeve shirt	65% polyester 35% Cotton	Outer	0.635 & 0.660 on the button fold 0.198 & 0.196 on rest of the shirt
Female Mannequin	Dark green	60% Cotton & 40 % Modal	Inner	0.259, 0.30, & 0.30 Mean = 0.286
	Red, full sleeve	60% Cotton & 40 % Modal	Outer	0.302, 0.363, 0.279, 0.320 Mean = 0.316
				Collar border thickness = 2.433 mm. Width of border = 1 cm.
Human (Dr. Raj)	White undershirt	Cotton	Inner	0.254 mm (mean)
	"Arrow" Gray full sleeve shirt	60% Cotton & 40 % Polyester	Outer	Mean thickness over button flap = 0.702 Mean thickness in other areas = 0.290
	Light green full sleeve shirt	60% Cotton & 40 % Polyester	Outer	Mean thickness over button flap = 0.676 Mean thickness in other areas = 0.272
	Washed light blue jeans	--	Outer	Mean thickness at thigh position = 0.787 mm
	Light brown pants	65 % Polyester & 35% Rayon	Outer	Mean thickness at thigh position = 0.309

Table 2-2: Locations of the two types of radiometers on the mannequins

Type of Mannequin	Type of radiometer	Location of radiometer		Remarks
		Position	Height above ground (cm)	
Male	Infrared radiometer, MedTherm Model 21325A with 1 mm thick Zn-Se window.	Under the chin	155.1	Protruding outside the clothing by about 5 cm.
	Heat flux transducer, MedTherm model # 21037.	On the chest	150.0	Placed between the skin and the inner clothing
Female	Infrared radiometer, MedTherm Model 21325A with 1 mm thick Zn-Se window.	Under the chin	146.0	Protruding outside the clothing by about 5 cm.
	Heat flux transducer, MedTherm model # 21037.	On the chest	140.9	Placed between the skin and the inner clothing

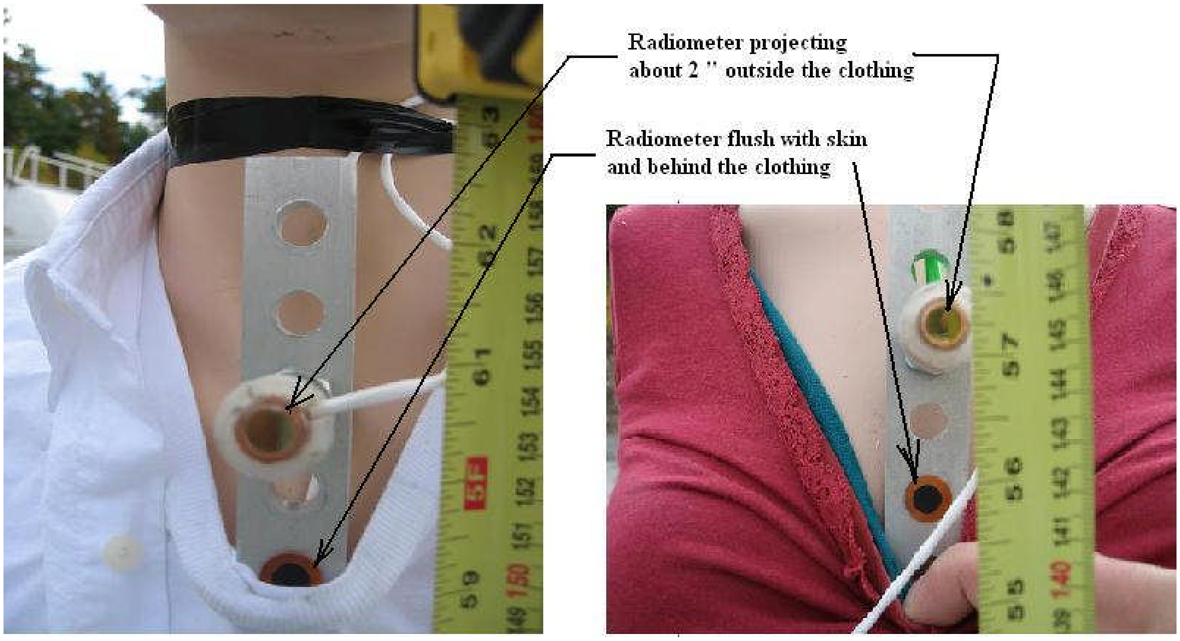

Figure 2-7A: Male mannequin

Figure 2-7B: Female mannequin

Figure 2-7: Picture showing the locations of radiometers outside and inside the clothing of mannequins

2.3.4 <u>Handheld radiometer</u>

A handheld radiometer was also used in these tests. This radiometer, made by the Hukseflux Thermal Sensors B.V., of Netherlands (model # HF03) with digital readout unit (model LI18) displays the incident radiant heat flux value in real time on the screen. The range of the instrument is 0 to 10 kW/m^2. The instrument averages the input radiant heat flux over 0.1 s intervals and displays the data on the screen. The instrument and the method of use are illustrated in Figure 2-8

The readout unit can also be connected by a serial port to a computer; however, the in-built program records the data only once every 10 seconds and provides the average heat flux over the 10 s interval. This unfortunately is not accurate enough to record the fast changing variations in the heat flux level during the exposure of a person over a short time interval (of the order of 30 seconds) to a LNG fire in variable wind conditions. This is especially unfortunate when trying to understand the effect on a person exposed (as closely as possible to the regulatory criterion heat flux of 5 kW/m^2) under varying heat flux conditions caused by wind-induced variability in the fire plume tilt and direction (resulting in fast changing radiant heat flux value at the observer position).

Figure 2-8: Handheld radiometer and illustration of its use in the field

2.3.5 Thermocouples

Several type J (32 ^{o}F to 1000 ^{o}F) thermocouples were used to measure temperatures at different locations during the tests. These locations included, (i) atmospheric air temperature just in front of the mannequins, (ii) temperature just above (1- 2 mm) the outer clothing of the mannequins, (iii) temperature in the space in between the skin of the mannequin and the inside surface of the inner clothing. The types and specifications of thermocouples used are indicated in Appendix A.

It is noted that no special care was taken to identify the exact location of the beads of the thermocouples. For example, the thermocouple “in contact” with the outer surface of the outer clothing of the mannequin was some time touching the clothing and some times one or two millimeter above the surface. Similarly, the “inner” thermocouple behind the inner clothing was placed behind the clothing. It is not therefore certain whether this thermocouple read the temperature of the air between the mannequin skin and the inner clothing surface or the skin temperature of the mannequin.

Dr. Raj also used a thermocouple close to his skin during his tests to determine the maximum radiant heat that he could withstand. This thermocouple was placed behind the undershirt close to his chest. Very likely, the thermocouple was touching his skin; it could also have been measuring the air temperature between his skin and the clothing, or the inner surface temperature of the underclothing.

2.3.6 Meteorological tower

The atmospheric temperature, wind speed and relative humidity near the test site were measured using the Vantage Pro2™ Plus weather station manufactured by Davis Instruments of Hayward, CA. The meteorological data instruments were on a tripod and located about 2 m above the local ground. The station was located at an approximate distance of 30 m (100 ft) from the center of the fire so that any micro-meteorological effects created by the fire did not influence the atmospheric data gathered by the instrument. The data gathered by the instruments were down linked, in real time, by radio communication to and stored in a data display console (Vantage Pro2™ Console). The data were stored at 1second intervals. The stored data were downloaded through a USB connection between the console and a laptop computer at the end of the day. Additional details of the weather instruments are provided in Appendix A.

2.3.7 Other instruments

The data from thermocouples and radiometers were fed to a National Instrument Data Acquisition and Control Module (Model # NI-SCXI-1600). The input into the module was through 32-channel, milliVolt signal amplifier (Model # NI-SCXI-1102), which mates with the Channel Isothermal Terminal Block (Model # NI-SCXI-1303). The data acquisition module (DAQ) receives the input milliVolt DC signals, conditions and digitizes the signals. These data together with internal clock generated time data are fed to a laptop computer through a USB port.

The digital data are stored and displayed using the LabVIEW™ software system developed by National Instruments. This software tool is used in the industry for design development, control and testing of data systems. The system provides built-in I/O and interactive user interface controls for data acquisition, manipulation, display and plotting as well as active control of the equipment based on the value of the data. Additional details of the DAQ are provided in Appendix A.

2.4 Description of Test Procedure

Most of the LNG fire tests were conducted in conjunction with the firemen training program during which the firemen were provided hands-on training in approaching and extinguishing a LNG pool fire on land with dry chemical powder and also in vapor control using fine spray water nozzles. Radiant heat flux measurements were made during the initial part of the firemen training when the fire was not “polluted” by any extinguishing agents.

Table 2-3 provides information on the test dates, number of test conducted, the weather conditions at the time of each test and other relevant information. The tests of 10/21 and 11/2 were conducted exclusively for the sake of taking radiant heat exposure data (no associated firemen training). Table 2-4 indicates the conditions of the test and the mannequin clothing parameters that were used in the tests.

Table 2-3: Summary of test conditions

Dates in 2006	Test begin time	# of fire tests(1)	Overall duration of each fire test (min)	Depth of LNG in the dike at ignition (inches)	Atm. Air Temp (°F)	Relative Humidity (%)	Mean wind speed (kph)	Weather condition & other Remarks
09/25	14:00	-	30	NA	63	60	1 - 3	Bright sunny day. Low winds. Fires lit primarily for the training of firemen. ***[Tests conducted to check out the instruments. No data taken].***
09/28	13:30	2	30	NA	70	55	1 – 6	Cumulus clouds, otherwise bright sun.
10/05	14:00	1	30	13	71	31	3.0	
10/19	13:25	2	30	13	61	61	1 - 2	
10/21	10:45	2	30	14	49	49	2, 6, 13, 24	Blue sky. Very gusty winds. Highly variable directions of wind
11/02	13:30	1	30	14	47	75	1 - 6	It rained in the morning. At the time of the test initiation the sky was clear, but gusty winds and variable direction

***Note**: (1) Number of fire tests implies the number of times the pool was ignited to form a pool fire.*

In each test the following test procedure steps were followed.

1 The distances from the center of the dike were measured and traffic cones were set up at 20 ft, 30 ft, 40 ft and 50 ft from the center of the dike[2]. These distances were set off in a direction perpendicular to the direction of the wind at the time of the test.

2 The instrumented mannequins were set up initially and temporarily at about 30 ft distance up-wind from the fire center. Before recording data, and after the fire was lit these mannequins were moved to a location where the handheld radiometer indicated a heat flux level close to 5 kW/m^2.

3 About 4 m^3 (1000 gallons) was continuously spilled into the dike over a period of about 15 minutes. The spill was through the spill pipe at the center of the dike, which was connected to a LNG tank located about 150 m (500 ft) away, on the farther side of the observation deck.

4 The vapors generated during the spill were managed by directing two water hose streams on both sides of the dikes to warm the vapors and to disperse them away from the dike (and the visitor deck) into the woods behind the dike. Care was taken to ensure that no water spray from the stream actually went into the dike with LNG in it.

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[2] Only in the test of 9/25 the traffic cones were set up at 10, 20, 30 and 40 ft distance from the edge of the dike.

5 When the boiling was reduced significantly (about 30 minutes after the initiation of the spill) and the vapor generation was at a minimum, the dike was approached and the relatively quiescent liquid pool depth was noted.

6 A fireman with a propane torch with a long stem effected the ignition of the pool.

7 Simultaneously, the recording of the data from the radiometers was initiated on the laptop computer.

8 Dr. Raj (the experimenter), in civilian clothes and holding the hand held radiometer at the navel level and with the plane of the heat flux sensing element about 6 inches in front of him, approached the fire. A fireman in bunker gear accompanied Dr. Raj, and was always by his side. This was intended to provide the experimenter assistance and aid in an emergency, if one occurred. The experimenter approached the fire until the radiometer read 5 kW/m^2. Because of the wind effects and the constant shifting of the fire plume in different directions, he would move forward or backward trying to maintain the reading on the handheld radiometer as close to 5 kW/m^2 as was possible. Figure 2-9 shows a picture of Dr. Raj approaching the fire accompanied by a fireman next to him. Figure 2-10 shows the location (at the cone 30 ft from the dike center) when the handheld radiometer was reading 5 kW/m^2 heat flux.

9 In general, the data-taking phase of the fire test was about 5 to 10 minutes.

10 When data gathering was completed the firemen training would begin with the demonstration of the proper use of dry chemical extinguishing agent on a burning pool of LNG.

11 If significant depth of LNG was still available, steps 5 through 9 were repeated. In some cases the dike was again filled after allowing sufficient time for it to cool after a fire test.

Figure 2-11 shows the details of how the Medtherm radiometers are strapped on to the author. In addition, Figure 2-12 shows another view of the author in civilian clothes approaching the fire with the Medtherm radiometers being strapped on to him.

Table 2-4: Parameters varied in the tests

Date in 2006	Distance from dike center (ft)	Test #	Test parameters/conditions
28 Sep	32	1	*Double layer clothed mannequins exposed to radiant heat* Inner radiometer on male mannequin on the stomach looking through the button flap on the shirt. Inner radiometer on female mannequin on the stomach looking through the bulge of the two layers of tight fit clothing.
	40	2	
		3	
5 Oct	40	1	*Double layer clothing* – Only male mannequin used. Also *Raj Exposure:* with half sleeve white shirt and undershirt. Only body temperature data recorded (malfunction of radiometer on Raj)
		2	
		3	
	25 - 35	4	*Raj exposure:* Heat flux data recorded from handheld radiometer. Frequency of recording only once in 10 s, not very accurate.
19 Oct	30	1	*Exposure of double layer clothed mannequins to radiant heat* Inner radiometer on male mannequin looking through thicker part of the button flap. Inner radiometer on female mannequin looking through the thicker neck border of blouse. Raj also exposed but only body temperature data recorded (button type radiometers failed to work).
		2	*Single layer clothing* on mannequins (white shirt on make and red blouse on female) + Raj exposure- recorded only temperature data.
	40	3	
	30 - 40	4	*Raj exposure*: Hand held radiometer data recorded. 2 trials of exposure
21 Oct	31	1	*Exposure of double layer clothed mannequins* to radiant heat
		2	*Single layer of undershirt* clothing only on the mannequins
		3	*Single layer of undershirt* clothing only on the mannequins + single sheet newspaper in front of one of the mannequin radiometers
21 Oct	25 – 32	4	*Exposure of Raj : Body temperature data only* (Radiometers did not work)
		5	***Exposure of Raj*** with Medtherm radiometer + body temperature measurements
		6	***Exposure of Raj*** with Medtherm radiometer + body temperature measurements
2 Nov	30	1	*Double layer clothed mannequins exposed to radiant heat* Inner radiometer on male mannequin looking through thinner parts of clothes. Inner radiometer on female mannequin looking through the thicker neck border of blouse.
		2	*A single sheet of newspaper* is held in front of female mannequin for some time. Both mannequins had double layer clothing
		3	*Two sheets of newspaper* held in front of female mannequin. Both mannequins had double layer clothing
		4	*Single layer clothing on the mannequins*. Also, long duration (300 s) exposure of the female mannequin outer radiometer obscured by one and two sheets of newspaper in front
2 Nov	25 – 35	5	***Exposure of Raj*** with Medtherm radiometer on the shoulder level, outside of two layers of clothing (long sleeve outer shirt and inner white undershirt). No mannequin data taken during these tests.

Note: (1) Double layer of clothing on male mannequin = White outer shirt + white undershirt
(2) Double layer of clothing on female mannequin = Red blouse outside + green undershirt + bra
(3) Single layer of clothing on male mannequin = White outer shirt
(4) Single layer of clothing on female mannequin = Green undershirt + bra
(5) Tests were video filmed only on 09/28, 10/05 and 11/02.

Figure 2-9: The author approaching the fire holding the handheld radiometer

Figure 2-10: A location where the handheld radiometer indicated a 5 kW/m^2 radiant heat flux (at about 30 ft from dike center)

Figure 2-11: Picture showing the strapping arrangement of the Medtherm fast acting radiometers onto the author

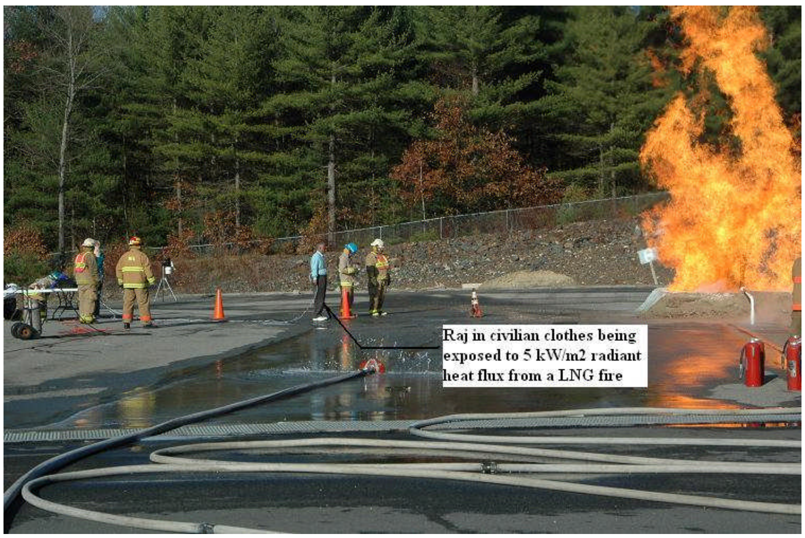

Figure 2-12: Another view of the author in civilian clothes facing the fire at the location of 5 kW/m^2 heat flux (at about 30 ft from dike center)

Chapter 3

Experimental data from mannequin & human exposure[3] to LNG fire

In this chapter the data gathered in this test series are indicated and the results are discussed. Three types of tests were conducted, namely, (i) Exposure of mannequins clothed with civilian clothing to the radiant heat flux from a LNG fire. The radiant heat fluxes outside the clothing and in between the inner clothing and the mannequin skin were measured. (ii) Effect of obstruction by one or more sheets of a newspaper in front of the mannequins on the radiant flux incident outside the clothing, and (iii) Exposure of a human being wearing normal civilian clothing to the radiant heat flux from the fire to determine the level of radiant flux that can be tolerated without any injuries and the duration of such exposure.

3.1 Mannequin exposure tests: Radiant heat attenuation by clothing

A number of trials were conducted to determine the effectiveness of ordinary civilian clothing in attenuating radiant heat transmission through the clothing. The purpose of the experiments was to obtain baseline data on the effectiveness of ordinary clothing worn by people in their daily routine.

The effectiveness of clothing in single layer configuration (outer shirt or undershirt only) and double layer configuration (outer shirt + undershirt) were investigated. A male mannequin and a female mannequin with the above configuration of clothing were used. The difference between the male and female mannequin lies in how the clothing was worn by each mannequin; the male clothing was loose fitting (with the outer shirt hanging out of the pant) and the female mannequin's outer shirt was tucked inside the pant. In addition, the female mannequin clothing were of the tight fitting kind thereby reducing the air gap between the inner and outer clothing (when the inner clothing was used). No measurement was made of the size of the air gap between the inner clothing and the skin of the mannequins or between the inner and outer clothing.

The scope of the study was limited due to the constraints of time and budget. The data gathered was limited to that from one type and one color of clothing on each mannequin. No attempt was made to use clothing of different thicknesses, different colors, weaves, material, types (summer, winter, etc) or systematic variation in the width of the air-gap between inner and outer clothing.

Both the male and female mannequins were located at a fixed distance (from the fire center) in each test and the radiant heat incident on the outside and inside the clothing were recorded. In general, tests were conducted with (i) two layers of clothing (outer shirt and inner undershirt) on both mannequins, and (ii) single layer clothing, with either only the outer garment or only the inner garment. The location of the inner radiometer was such that in different tests, its line of sight would go through either the thinner parts of the clothing or through the thicker button flap

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3 The exposure of the human subject did not result in any temporary or permanent injury (to the exposed skin or to any other part of the body) during or after the completion of each test.

of the outer shirt. Tests were also conducted to determine the effect of a simple object, such as a newspaper (one or two sheets) held in front of the mannequins obstructing the radiant heat input to the outer radiometer. In these tests the radiant heat flux incident on the outside of the clothing and incident on the (mannequin) skin protected by the clothing was measured as a function of time. Also measured were the temperature of the air, temperature just above the outer clothing and temperature between the "skin" and the inner garment.

Table 3.1 summarizes the parameters varied in the tests conducted with clothing on the mannequins and exposure of the mannequins to a LNG fire.

3.2 Results from tests of exposure of clothed mannequins to LNG fire

The raw heat flux data from the Medtherm wide-angle radiometers (located outside the clothing and in between the skin and inner clothing of the mannequins) were recorded at 0.1 s intervals. Also recorded in most cases were temperature data from three thermocouples located on the outside of the clothing to measure the air temperature, very close to the outer shirt surface, and between the "skin" and the inner garment. These data have been processed and plotted. The data for all tests are presented in Appendix C in the form of graphs of radiant heat flux vs. time, and temperatures recorded at different parts of the mannequins vs. time.

It is found that the heat flux recorded by the outside radiometer is always higher than that recorded by the radiometer whose view is obstructed by the clothing. That is, the clothing material attenuates the radiant heat flux going through it by absorption. Other effects that may be occurring at the clothing include radiant heat reflection and scattering. The attenuation factor (AF) for the effectiveness of clothing of different thickness is defined as follows:

AF (Attenuation factor) = Ratio of Radiant heat flux recorded by the radiometer in front of the clothing to that recorded by the radiometer behind the clothing (in between the skin and the inner clothing) (1)

In the graphs presented in Appendix C, the value of the attenuation factor (AF) is also plotted as a function of time for all tests. Also provided in Appendix C are the data for the attenuation factors for newspaper sheets (held in front of the radiometers).

In all tests, the two mannequins (male and female) were located side by side at the same distance from the fire center. The difference between the clothing on the male and the female mannequins (in addition to colors of the clothing) was in the looseness of fit. In the case of the male mannequin the clothing was loose (outer shirt not always tucked into the pant), whereas the clothing on the female mannequin was always tight (outer shirt tucked into the pant). It is hypothesized that because of the loose fitting clothing on the male mannequin, the air gap between the outer shirt and the inner undershirt was thicker than in the case of the female mannequin.

Figure 3-1 shows a typical temporal record of the radiometers outside and inside the clothing for the male mannequin. Figure 3-2 shows the same type of record for the female mannequin. The results in both these figures indicate the radiometer readings (outside the clothing and inside the

Table 3.1: Test details of the exposure of clothed mannequins to LNG fire

Test Date in 2006	Expo-sure test #	Mean flame height [m]	Distance to mannequins from fire center [m]	Description of clothing on the mannequins				Remarks
				Male		Female		
				Outer	Inner	Outer	Inner	
09/28	1	5.1	9.8	White shirt	White under-shirt	Red shirt	Green under-shirt	Inner radiometers at stomach level
	2	4.2	12.2					
	3	5.1	12.2					Radiometer data not recorded. Instrument malfunction
10/05	1	7.2	12.2	White shirt	White under-shirt	Mannequin not used		Inner radiometers just below chin level
	2	6.6	12.2					
	3	5.5	12.2					
10/19	1		9.8	White shirt	White under-shirt	Red shirt	Green under-shirt	The data from the inner radiometers on both the male and female mannequin are suspected to be erroneous. The wiring may have been loose.
	2		9.8	Not used	White under-shirt	Not used	Green under-shirt	Radiometers on the chest
	3		12.2	Not used	White under-shirt	Not used	Green under-shirt	Radiometer data recording failure
10/21	1			White shirt	White under-shirt	Red shirt	Green under-shirt	Inner radiometer on the male mannequin viewing through two thin clothing layers(black outer + white inner) . Inner radiometer on the female mannequin viewing through the undershirt and button flap of the outer clothing.
	2			Not used	White under-shirt	Not used	Green under-shirt	Only the inner shirts were used. Test 2: No newspaper shield used Test 3: Single sheet newspaper held in front of both radiometers on the male mannequin
	3							
11/02	1	6.7	9.7	White shirt	White under-shirt	Red shirt	Green under-shirt	Inner radiometer on the male mannequin viewing through two thin clothing layers. Inner radiometer on the female mannequin viewing through the undershirt and button flap of the outer clothing. Also, briefly one and two sheets of a newspaper was held in front of the outer radiometer of the female mannequin. Test 1: No newspaper Test 2: One sheet of newspaper Test 3: Two sheets of newspaper Both single sheet and two sheets of newspapers were used in the same test at different times.
	2	5.0	9.3					
	3	5.1	8.4					
	4	5.0	8.8	White shirt		Red shirt		

inner clothing) for the case in which both mannequins had double layers of clothing. The inner radiometer reading can be interpreted as that radiant heat flux incident on the skin of the mannequin. The difference between the two mannequins are that in the case of the male mannequin (Figure 3-1) the inner radiometer view is through the two thin sections of the undershirt and the outer shirt, whereas in the case of the female mannequin (Figure 3-2) the inner radiometer view is through the thinner undershirt and the thicker outer shirt collar material. From the two figures it is evident that the outer radiometers read the same heat flux (as it should be because the mannequins were located at the same distance from the fire center and next to each other), whereas the inner radiometers read different fluxes. The attenuation factor in the case of the female mannequin (with thicker cloth through which the radiant heat flux has to go through) is higher than in the case of the male mannequin. That is, the thicker the clothing material, the higher is the attenuation of the radiant heat flux.

Table 3-2 provides the details of the data collected on the mannequin exposure to LNG fire heat flux. This shows the statistical average and standard deviation values (over the duration of exposure) of the incident heat flux, and the average and standard deviation of the measured attenuation factor. The condition of exposure and the thickness of the clothing through which the inner radiometer "looks through" are also indicated. Figure 3-3 summarizes the statistical data on the attenuation factor plotted as a function of the cloth thickness. A few anomalous data are also indicated. Based on the results presented in Figure 3-3, the following dimensional correlation is obtained for the clothing attenuation factor (for the clothing used in these tests)

$$AF = 1.82 + 0.875 * t \tag{2}$$

where, t is the clothing thickness in millimieters.

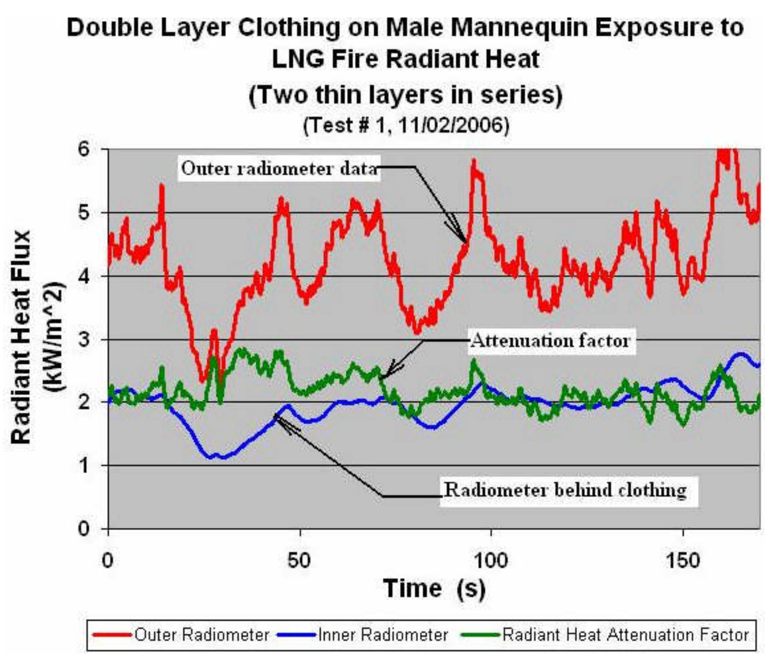

Figure 3-1: A sample record of radiometer data from the male mannequin

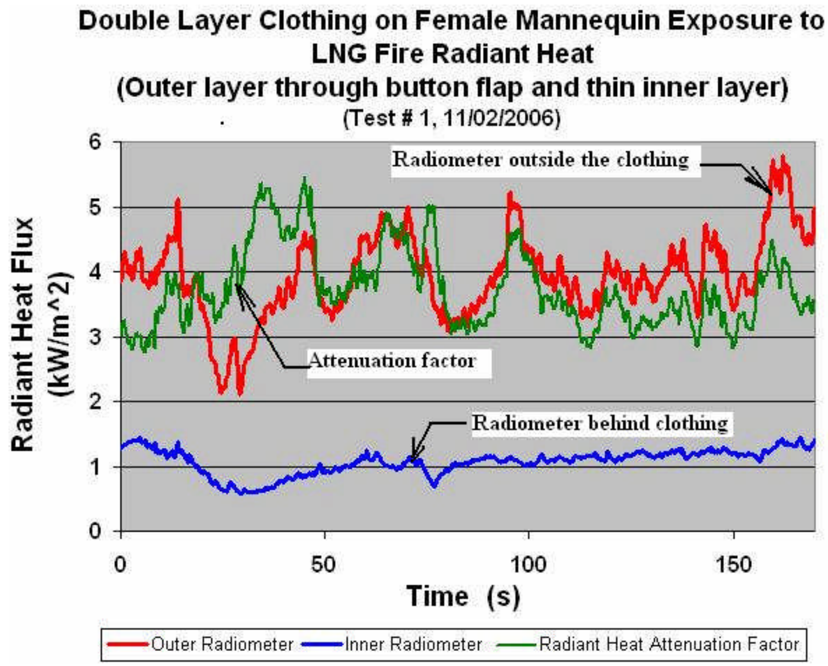

Figure 3-2: A sample record of radiometer data from the female mannequin

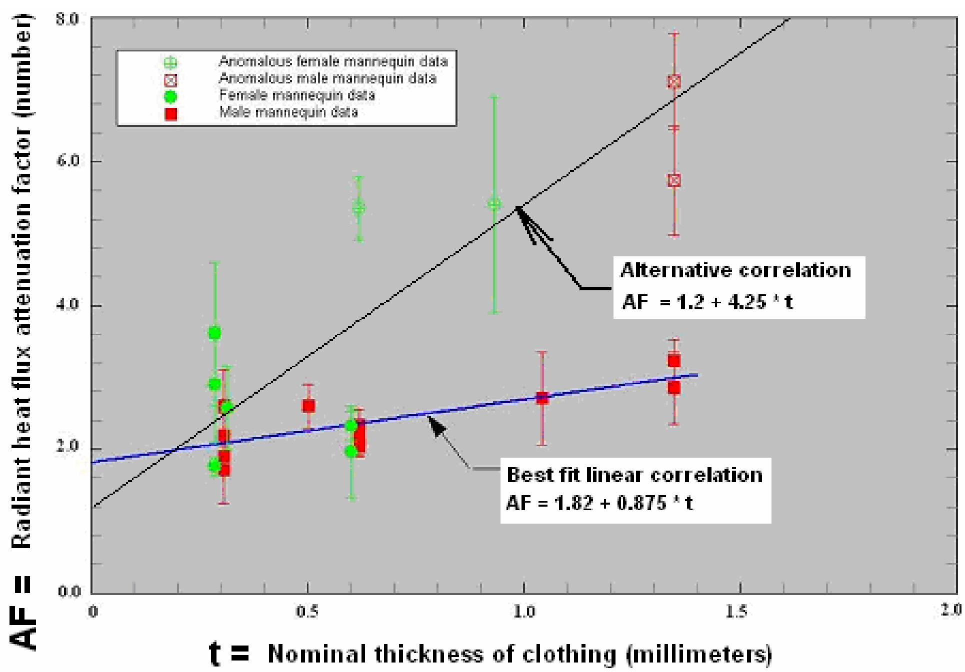

Figure 3-3: Radiant heat flux attenuation factor vs. clothing thickness

Table 3.2: Attenuation factors for different thickness clothing at different exposure levels

Test Date in 2006	Test #	Mannequin type	Inner radiometer view through	Overall clothing thickness(1)	Averaging time interval for heat flux and attenuation factor statistics	Mean outside radiant heat flux	Attenuation factor from inner & outer radiometer data		Remarks
				(mm)	(s)	(kW/m^2)	(Mean)	(Std. Dev)	
9/28	1	Male	Inner & outer clothing over the belly. View through outer button flap	1.347	0-100	2.0	5.73	0.76	Normal air gap between inner and outer clothing
	2			1.347	0-20	1.0	7.11	0.68	
	1	Female	Inner & outer clothing over the belly. View through thinner parts of both clothing	0.602	0-100	2.0	2.33	0.20	Inner & outer clothing layers very close and tight. Inner radiometer bulging on the two clothing.
	2			0.602	0-20	1.0	1.97	0.64	
10/5	1	Male	Double layer clothing. Inner radiometer view through the outer shirt button flap	1.347	15 - 300	3.92 ± 1.1	2.86	0.50	Radiometers at chest level
	2			1.347	0 - 40	3.75 ± 0.31	3.23	0.29	
	3		Only outer shirt. View through button flap.	1.041	0 - 120	2.97 ± 1.41	2.71	0.65	
10/19	2	Male	Only inner white undershirt used.. View through thin part of clothing	0.306	0 - 70	6.81 ± 0.94	1.71	0.46	Radiometers at chest level
	2	Female	Only inner green undershirt used. View through thin part of clothing	0.286	0 - 70	6.81 ± 0.94	1.76	0.13	
10/21	1	Male	Black outer + white under shirt. Two thin parts of the clothing in series	0.503	0 - 290	3.9 ± 0.7	2.60	0.30	Radiometers at chest level
	2		White undershirt only	0.306	0 - 250	3.8 ± 0.6	2.20	0.30	
	3			0.306	0 - 66	3.6 ± 0.5	2.60	0.50	

	1	Female	Black outer + green under shirt. View through button flap of outer black shirt.	0.931	0 - 290	4.2 ± 0.7	5.40	1.50	Radiometers at chest level
	2		Green undershirt only	0.286	0 - 250	3.9 ± 0.6	3.60	1.00	
	3			0.286	0 - 350	4.0 ± 0.6	2.90	0.80	
11/2	1	Male	Double layers. View through thin parts of the clothing	0.619	0 - 170	4.21 ± 0.73	2.17	0.25	Radiometers at chest level
	2			0.619	0 - 50	4.49 ± 0.3	2.05	0.14	
	3			0.619	0 - 55	4.68 ± 0.87	2.34	0.22	
	4		Single outer shirt only. View through the thin part of the shirt	0.306	0 - 300	4.16 ± 1.14	1.91	0.14	
	1	Female	Double layers. View through collar border thickness on outer and thin part of the inner clothing	2.719	0 - 170	3.93 ± 0.64	3.74	0.61	Radiometers at chest level
	2			2.719	28 - 50	4.13 ± 0.45	4.31	0.62	
	3		Double layer clothing. View through thin parts of the clothing	0.619	41.5 - 55	5.36 ± 0.21	5.35	0.44	
	4		Single layer outer red shirt only. View possibly changed during test, initially through the collar flap and later through the thin part of the clothing	0.316	0 - 15.5	3.7 ± 0.46	2.57	0.58	

3.3 Data from tests with newspaper sheets

Tests were conducted by placing one and two sheets of a newspaper at about 5 cm (2 inches) in front of the outside radiometer. The size of the newspaper sheet was about 30 cm x 30 cm and this sheet was held on a coat-hanger wire frame. During the experiment it was ensured that the newspaper obstructed the view of only one outsider radiometer (of the two mannequins) with the other on-obstructed outside radiometer (on the other mannequin) measuring the radiant heat flux value at the location of the mannequins. Tests were repeated with and without the newspaper to ensure that both outside radiometers were measuring the same heat flux when unobstructed.

Figure 3-4 shows a typical radiant heat flux record of the unobstructed radiometer and that of the radiometer in whose front the newspaper sheet was held. The considerable decrease in the heat flux behind the newspaper can be clearly seen even in the case of a single sheet of newspaper (of thickness 0.076 mm ($3x10^{-3}$ inches). Other data from newspaper obstruction are indicated in Appendix C.

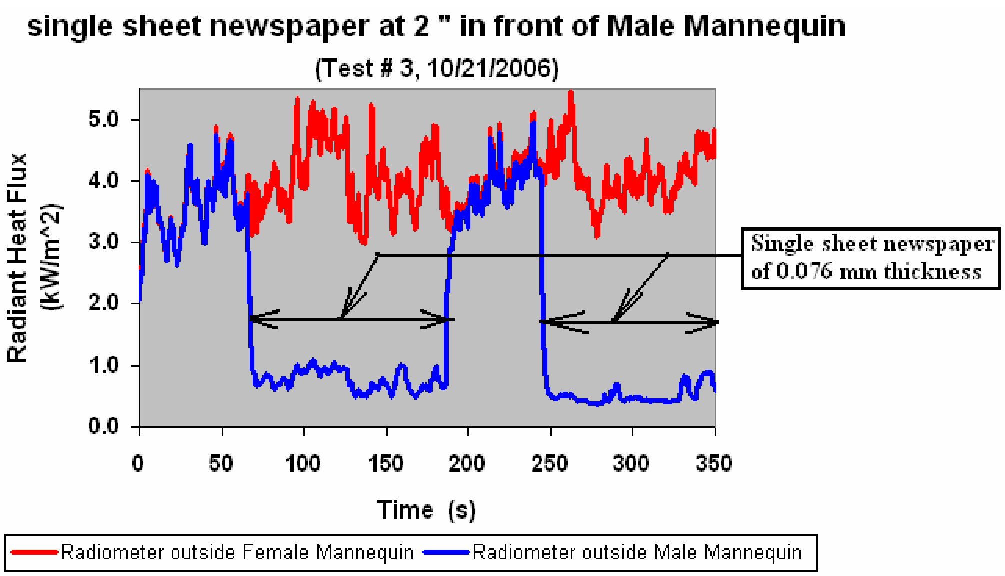

Figure 3-4: Attenuation of radiant heat flux by a single sheet of newspaper

Table 3-3 summarizes the newspaper sheet attenuation factor values obtained in the tests and the heat flux values to which the sheets were exposed. The same data are plotted in Figure 3-5.

It is seen that the even a single sheet of newspaper provides a substantial reduction in the radiant heat flux. That is, a single sheet can provide a substantial relief from exposure to radiant heat flux from a fire. The attenuation factor increases as the newssheet thickness increases. Also, it is seen that the attenuation factor is dependent upon the magnitude of the heat flux; as the heat flux value increases, the attenuation factor decreases indicating the decrease in the shielding effectiveness of the newspaper sheet at higher exposure levels. It is noted that at the level of concern for human exposure (5 kW/m^2) the attenuation factor for a single sheet is about 5.

Table 3.3: Attenuation factors for different thickness of newspaper sheets

Test Date in 2006	Test #	Overall newssheet thickness[1]	Averaging time interval for heat flux and attenuation factor statistics	Radiant heat flux	Attenuation factor from inner & outer radiometer data		Remarks
		(mm)	(s)	(kW/m^2)	(Mean)	(Std. Dev)	
10/19	2A	0.076	22 - 35	6.22 ± 0.67	3.58	1.74	1 sheet of newspaper
	2B	0.147	48 - 57	6.54 ± 0.33	4.29	2.04	2 sheets of newspaper
10/21	3A	0.076	66 - 186	4.1 ± 0.5	5.40	1.00	1 sheet of newspaper
	3B		245 - 359	4.2 ± 0.4	8.10	1.60	
11/02	2	0.076	0 - 28.1	4.13 ± 0.45	4.72	0.37	1 sheet of newspaper
	3	0.147	0 - 41.5	4.3 ± 0.63	11.75	1.43	2 Layer newspaper sheets
	4A	0.147	0 - 189	3.96 ± 0.7	9.10	1.69	2 sheets of newspaper
	4B	0.076	240.3 - 270	6.37 ± 1.07	5.40	1.00	1 sheet of newspaper

Note: All newspaper sheets were held about 5 cm (2 inch) in front of the radiometer

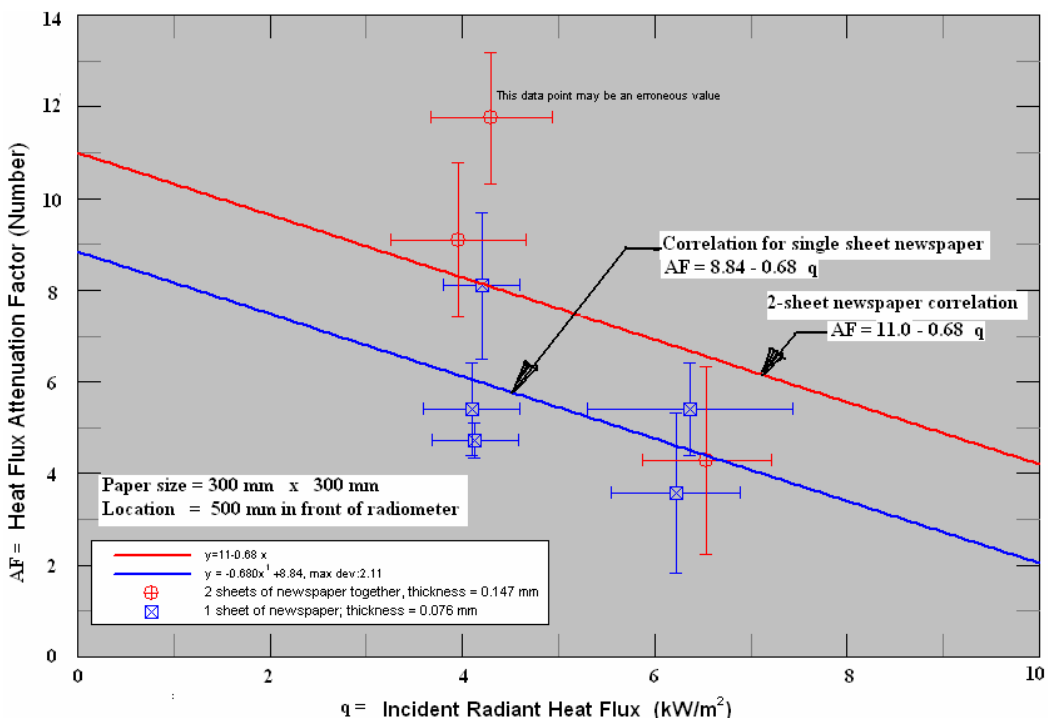

Figure 3-5: Radiant heat attenuation factor vs. newspaper sheet thickness

Based on the statistical results presented in Figure 3-5, a dimensional correlation of the following type is developed for radiant heat attenuation by newspaper sheets**.**

$$AF(newspaper) = 6.528 + 30.423\, t - 0.68\, q \qquad (3)$$

Where

AF	=	Attenuation factor by newspaper sheet
t	=	newssheet thickness in millimeters
q	=	Radiant heat flux in kW/m^2 incident on the sheet

3.4 Tests involving human exposure to radiant heat from the fire

The purpose of the human exposure tests was to determine the highest level of heat flux that a person in normal civilian clothing and unprotected skin could tolerate when suddenly exposed to the radiant heat from a LNG fire. The objective was to obtain baseline data from a live human being without causing any temporary or permanent radiant heat caused injury. By his own volition and on a completely voluntary basis the project manager and author of this report (Dr. Phani Raj) acted as the human subject for these tests.

These tests involved the subject, in civilian clothing (but accompanied on the side by a fireman in full bunker gear) going close to the fire until the reading on a handheld radiometer indicated a heat flux level close to 5 kW/m^2. The subject stayed at the location or ambulated towards or away from the fire depending upon whether the wind was tilting the fire plume away from the subject or towards the subject, respectively. The duration over which the subject could withstand the heat without pain or injury was noted.

Three different variations of the above procedure were used in these tests. In the first phase of the tests the author used only the handheld radiometer (see Figure 2-8, Figure A-8 and Figure A-9) and recorded on paper after the completion of the test recalling from memory the data displayed on the radiometer screen during the test. The handheld radiometer is capable of displaying incident heat flux data at 0.1 s intervals. No digital recording of the data on a computer was possible. In the second phase of these human exposure tests the handheld radiometer was connected to a computer through a serial cable. However, because of the software limitation, it could record on to a computer file only once in 10 seconds. The data recording in both the first and second phase was somewhat unsatisfactory. Therefore, a third phase of tests was implemented. In this third phase one Medtherm wide-angle radiometer (that was normally on the mannequins) was strapped on to the author using the same mounting bracket that was on the mannequin, and the readings from this radiometer were recorded digitally on a computer file at a rate of one record in each 0.1 s interval. In addition, in several of the tests, thermocouples were also placed both on the outside of the shirt as well as between chest or abdomen skin and the undershirt of the author to record, respectively, the temperature of the outer garment and the skin when exposed to the radiant heat.

The results of these human exposure tests are discussed in section 3.5.

3.5 Data from human subject exposure to radiant heat from a LNG fire

3.5.1 Qualitative observations

In none of the tests when the author (Dr. Raj) was exposed to the radiant heat from the fire did he experience severe pain or any type of burn on the exposed parts of the skin. Tests were conducted with full sleeve shirts, half sleeve shirts, both with undershirts and full pants. It was very difficult to maintain the incident heat flux level exactly at or even close to 5 kW/m^2 because of the shift in wind direction and the consequent fast response bending of the fire plume. Also, in some cases the natural turbulence created by the fire itself resulted in burst of energy in different directions. The human response action always lagged behind the variations in the heat flux at any given point, even though the author made an effort to maintain the reading on the handheld radiometer as close to 5 kW/m^2 as possible. In some cases, he was exposed to short bursts of heat flux (for 3 to 5 seconds) as high as 7 kW/m^2 and in other cases to as low as 3.5 kW/m^2.

When exposed to relatively prolonged durations (of the order of 10 seconds) to heat flux levels close to 5 kW/m^2 the sensation of heat was close to what one experiences in front of and close to a hot well established fire in a household fireplace. Heat flux levels of 6.5 kW/m^2 and higher begin to result in a sensation of pain on the unprotected skin within a very short duration (several seconds approaching 10 s). Even when exposed to long durations (of the order of 50 seconds) at levels less than 4 kW/m^2 or for less than 30 seconds at 5 kW/m^2 and higher no feeling of heat is felt on the skin protected by clothing. However, the body begins to sweat and maintain the body temperature at the normal human temperature.

Exposure for short intervals (of the order of tens of seconds) of time followed by very short time (less than a minute) away from the radiant heat flux levels of 3 – 5 kW/m^2, followed by another session of exposure to the fire, resulted in less tolerance to the radiant heat flux (both magnitude as well as duration). What the author noticed was repeated exposure without sufficient “cooling” time after each exposure resulted in the outer clothing getting ‘hot’ and the ability to withstand heat flux levels of 4 - 5 kW/m^2, lower. These observations are supported by documented data from the radiometers and thermocouples discussed below.

The author’s skin on the gullet became red in the final test by repeated exposure to the fire and the irritation due to this “redness” persisted for about 30 minutes after the completion of the test. There were no other temporary or permanent skin or other injuries to the author, even though the exposures were repeated several times in one fire test (without, as noted above, any prolonged cool down period) to levels as high as 4 kW/m^2 and with bursts of 5 or 6 kW/m^2 and exposure times measured in 30 to 50 seconds.

3.5.2 Handheld radiometer data

The data recorded (during the first few days of tests and based on the author’s memory immediately following the tests) from the visual of the handheld wide-angle radiometer are indicated in Table 3-4. Location of the subject, flame heights during the time of exposure and the exposure time were obtained from the video records of the tests. The heat flux data are from the screen readings on the visual display of the radiometer and is based on the paper recording after the test. The range of heat fluxes indicated show the minimum and maximum displayed on the screen and do not necessarily indicate how long such levels were experienced. The mean heat flux values experienced may also not be very reliable since they are based on the best judgment of the subject and his memory. However, the data do indicate levels that are relatively high and the durations of exposure (measured from the films) quite long.

No data are provided from the digital recording of the output from the handheld radiometer since the recordings were unsatisfactory. This is because, the software only recorded once in 10 seconds (averaged the heat flux over that 10 seconds). Hence, in each session one got only 3, 4 or 5 data output, which, to say the least, was not very useful for the experiment of concern.

Table 3-4: Handheld radiometer data on human exposure to radiant heat[(1)]

Test Date in 2006	Expo-sure session #	Mean flame height [m]	Location of human subject[(2)] [m]	Mean radiant heat flux and [range] [kW/m^2]	Exposure duration[(3)] [s]
09/28	1	5.1	12	2.2 [2.1 - 2.9]	53
	2	4.2	8	4.4 [3.8 - 5.8]	17
	3	5.1	10.5	2.2 [2.7 - 5.8]	60
	4	5.9	11.0	2.2 [2.0 - 3.0]	103
	5	5.5	7.9	4.4 [3.8 - 6.0]	22
	6	4.3	7	4.4 [3.8 - 5.8]	21
	7	5.5	7.9	2.2 [2.0 - 3.2]	120
10/05	1A	7.2	9.3	5.0 [4.9 - 6.2]	26
	1B	7.1	12.2	5.03 [4.0 – 8.0][(4)]	93
	2	6.6	11.1	5.0 [4.5 - 6.0]	42
	3	5.5	8.7	5.0 [4.9 - 6.2]	24
11/02	1	6.7	9.7	5.0 [4.9 - 6.2]	57
	2	5.0	9.3	5.0 [4.9 - 6.2]	16
	3	5.1	8.4	5.0 [4.9 - 6.2]	32
	4	5.0	8.8	5.0 [4.9 - 6.2]	20
	5	4.7	9.1	5.0 [4.9 - 6.2]	31

NOTES: (1) For more detailed data from the video films, see Appendix B.
(2) All distances are from the center of the dike. These distances represent the mean values during a test in which the subject moved closer to or away from the fire depending upon whether he received less than or higher than 5 kW/m^2 heat flux.
(3) No injury of any kind was sustained by the person exposed over the duration indicated in the table
(4) Based on measurements on the mannequin radiometer next to the author (See test # 1 of 10/5/2006).

3.5.3 <u>Data from Medtherm radiometers strapped on to the human subject</u>

The data recorded by the Medtherm wide-angle radiometers strapped on to the author (see Figure 2-11) when exposed to the radiant heat flux from the LNG fire are shown in Figure 3-6A, Figure

3-6B and Figure 3-6C. Each figure refers to a different test. Common to all the tests are that the exposure is quite above 3.5 kW/m^2, and in spurts above 5 kW/m^2 and the durations are long

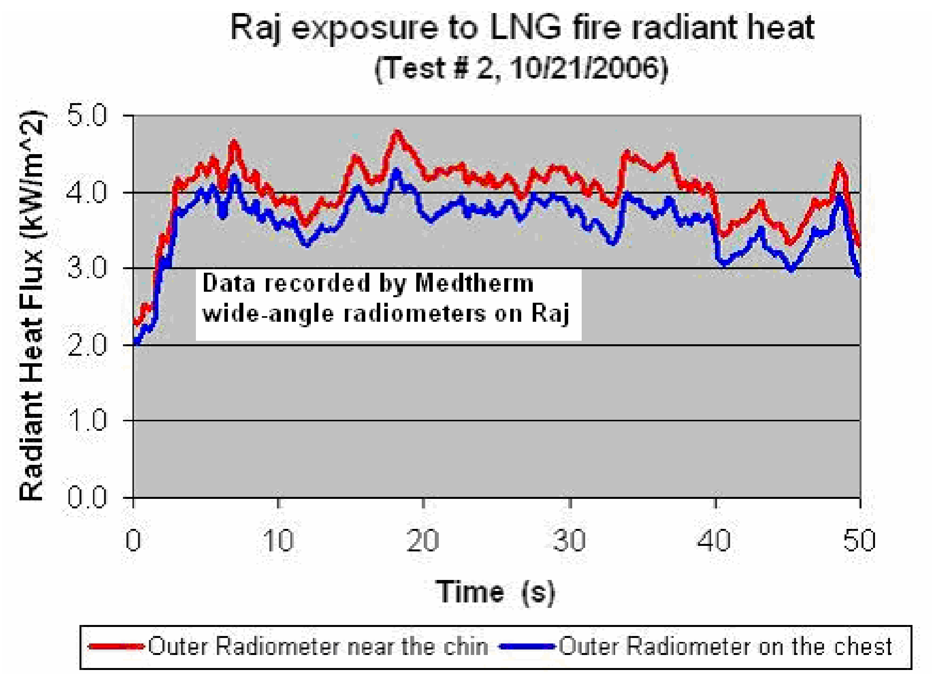

Figure 3-6A: Human exposure to a LNG fire radiant heat flux- test 2 of 10/21

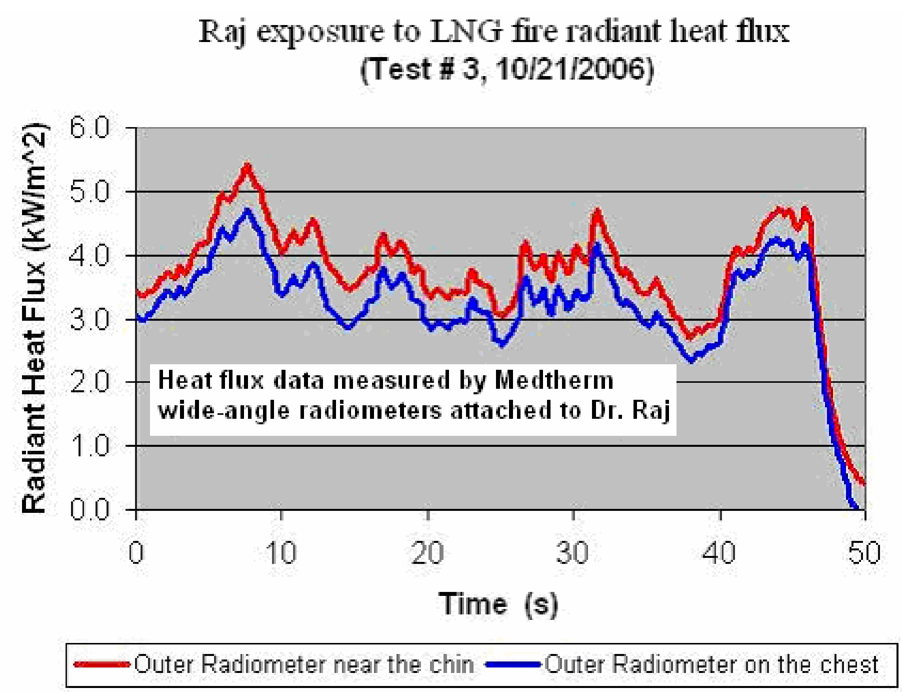

Figure 3-6B: Human exposure to a LNG fire radiant heat flux- test 3 of 10/21

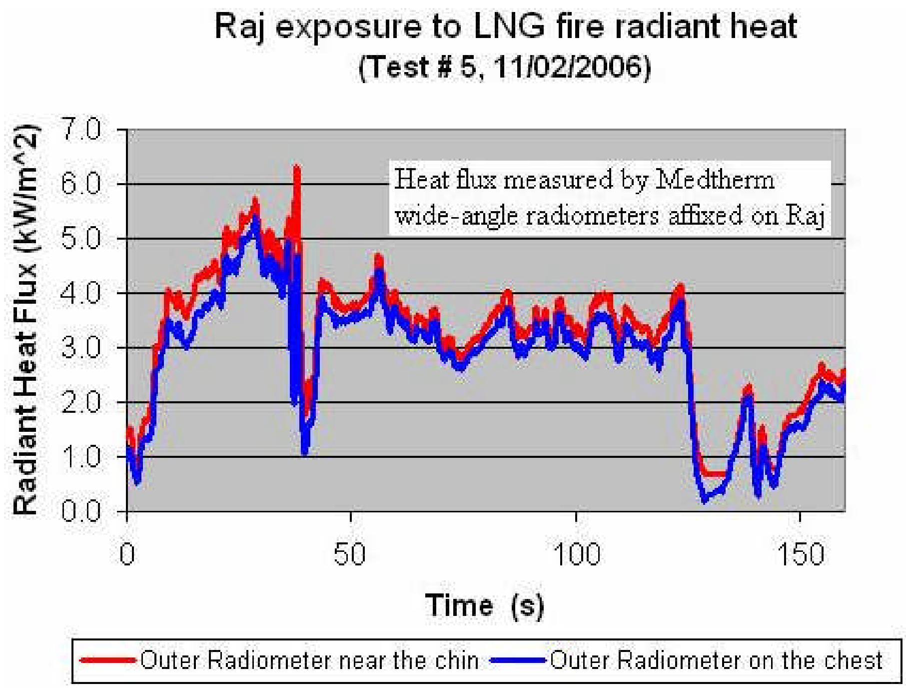

Figure 3-6C: Human exposure to a LNG fire radiant heat flux- test 5 of 11/02/06

(about 50 seconds in the first two and 120 seconds in the 3rd figure). As mentioned before, there were no injuries from any of these exposures and there certainly was no skin burn. In Appendix C are provided all data recorded during the human exposure experiments..

3.5.4 <u>Temperature data</u>

Temperatures were recorded on both mannequins and on the human subject. The temperatures were measured by thermocouples placed just outside the clothing and inside the clothing. In the case of the male mannequin as well as in the human subject the inside thermocouple was placed between the skin and the inner undershirt, either on the chest or on the belly. In the case of the female mannequin the inner thermocouple was placed between the skin and the bra. No special care was taken to place these thermocouples to read temperature at any special point or location. For example, the thermocouple inside the author's undershirt (once on the belly and other times on the chest) was dangling between the skin and the undershirt, some times touching the clothing and some times the skin. It is anticipated that the "inner" thermocouple measured the air temperature between the skin and the inner shirt or clothing in all cases. The outer thermocouple was attempted to be placed just above the outer clothing (and not touching it) by strapping it on with sticky tape. This did not always work as intended and the readings indicate that in many instances the outer thermocouple bead may have been touching the outer garment surface (which tends to heat up considerably after repeated exposure to the fire radiant heat).

In Figure 3-7 are shown several temperature measurements and a comparison between the temperature attained by a human skin behind clothing and a mannequin skin behind clothing. It is seen that the human skin temperature rises slightly but never goes above the normal human body temperature of 36.9 ^{o}C (98.4 ^{o}F). This is contrasted with the mannequin "skin" temperature, which rises rapidly (to a high of about 60 oC). This rise is attributed to the fact that the mannequin "skin" has no internal cooling mechanism as in the case of a human being who can sweat and whose blood circulation carries away the heat that is incident on the skin. The mannequin is made of fiberglass and it is a poor conductor of heat. The heat flux over the duration of this exposure was about 4 kW/m^2 (see Table 3-2 for the test # on the date specified). Other similar human skin and mannequin "skin" temperature data recorded in the tests are indicated in Appendix C.

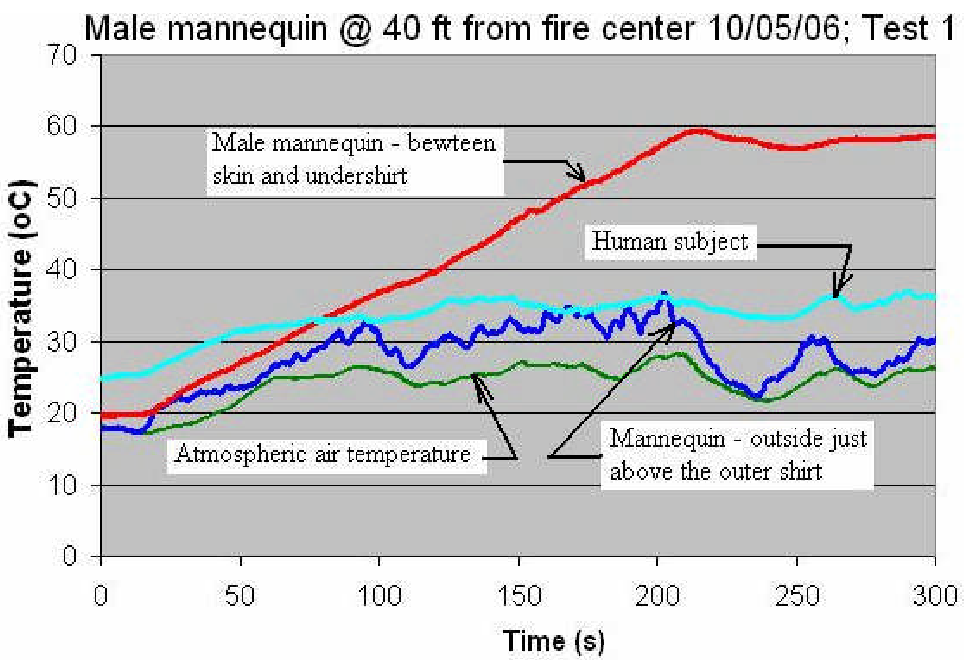

Figure 3-7: Comparison of mannequin and human skin temperatures for exposure to the same fire at the same distance

It is seen that repeated exposure to the fire without the person or the mannequins being removed from the site (to cool off) between the times that that the data are taken result in much higher skin temperatures and outer clothing surface temperatures. For example, Figure 3-8 shows the temperatures measured on the author in the final stages of a test on 11/2/2006 when he had been exposed several times to the fire. The exposure was at a mean heat flux value of 3.8 kW/m^2 (± 0.7 kW/m^2 Std dev) for over 120 seconds. As can be seen in the figure, while the air temperature is hardly above 20 ^{o}C, the human skin temperature of the skin protected by double layer clothing is approaching 40 ^{o}C. The temperature just on or above the outer shirt surface is not much higher than the ambient temperature. Figure 3-9 shows a similar mannequin skin behavior for heat flux exposure without much "cooling off period" between data taking and constant exposure to fire.

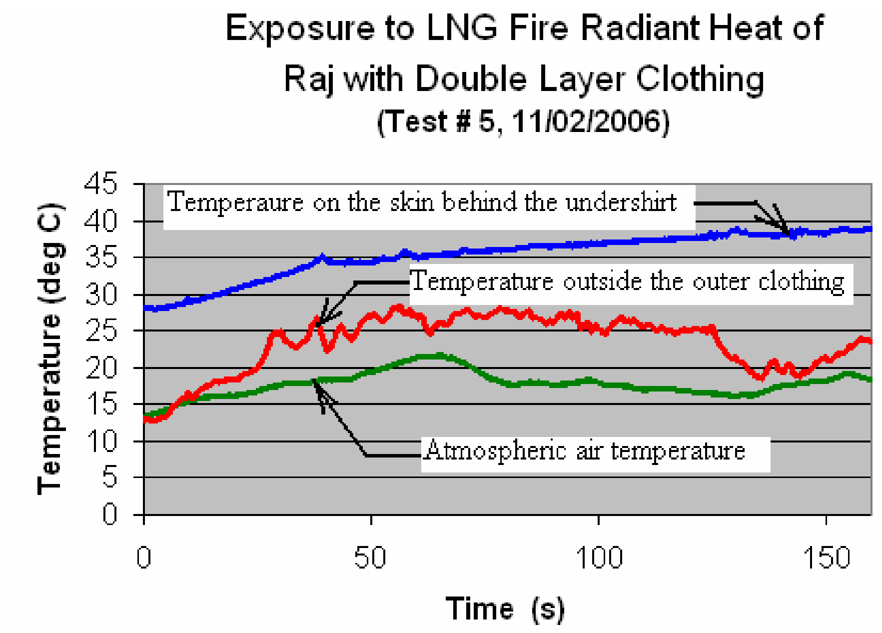

Figure 3-8: **Temperature of human subject skin after repeated exposure to fire heat flux without cooling off period between tests**

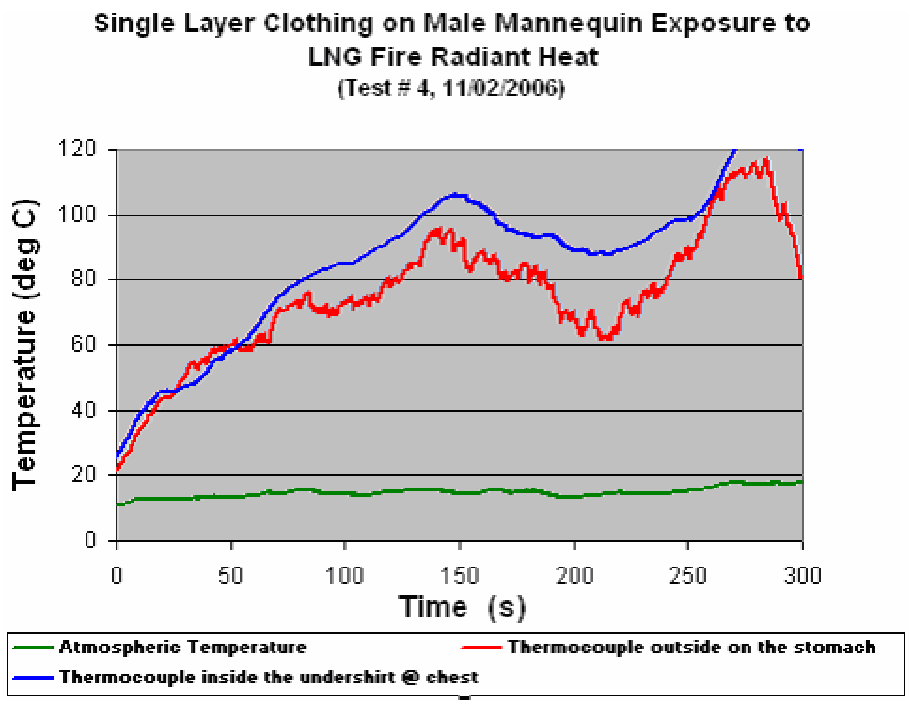

Figure 3-9: Temperature of mannequin skin after repeated exposure to fire heat flux without cooling off period between tests

Chapter 4

Findings, Conclusions & Recommendations

4.1 Findings and discussion of the results

Finding # 1: Ordinary civilian clothing, even a single layer clothing, provides a factor of at least 2 reduction in the magnitude of radiant heat flux reaching a person's skin for relatively long term exposures (of the order of minutes) at an exposure level of 5kW/m^2 or close to it.

The results in this report substantiate the above finding. Even single layer clothing such as an undershirt of thickness 0.2 to 0.3 mm (8 x 10^{-3} to 12 x 10^{-3} inches) reduces the heat flux by a factor greater than 2 for exposure time of minutes. The thicker the fabric the greater is the attenuation factor, reaching as high as 3 or 4. In the tests performed no attempt was made to determine the effect of the air gap between two layers of clothing. It is known from the heat transfer literature that air gaps do provide "insulating" characteristics to the clothes and help keep the person warm in winter. However, in this literature no test is reported where the effectiveness of air gap to reduce the magnitude of pure IR radiation (at the levels of 5 kW/m^2), for relatively short-term exposures has been studied. The objective of the tests indicated in this report was to determine the "protection" provided by ordinary civilian clothes under conditions encountered in the normal, daily lives of citizens.

It has been found that the magnitude of the attenuation factor (AF) varies between 2 and 3 for overall fabric thickness ranging from 0.2 mm to 1.5 mm, respectively. In one or two experiments, very high values of AF (as high as 6-7) were found. It is entirely possible that these high AF values are real because during these experiments the inner radiometer was actually "looking" though the thick button flap part of the outer shirts, where as in other cases, where we thought that the view was through the thick part of the shirt actually was not realized. Hence, the data points plotted in Figure 3-3 for thickness values of 1.05 mm and 1.47 mm (shown in red) are suspect rather than the higher AF values. An alternative correlation utilizing the higher AF values at thicker clothing values is also shown in Figure 3-3. Unfortunately, we did not have sufficient "control" in the experiment to make a definitive statement as to whether the correlation provided in equation 2 is valid or a higher AF correlation with thickness is needed. This could be the subject of any future research. However, suffice it to say that the correlation provided is very conservative in that it predicts lower (but significant) AF values with clothing thickness. It should also be noted that the thickness measure used in this report does not involve the consideration of the air-gap thickness. Future work should take this into account as well. It should also be noted that in this experiment the fabric quality (texture, smoothness, material, etc) or the color were varied over sufficiently wide values as to provide a picture of the effectiveness of different types of clothing. However, it is expected that any type of clothing would provide similar heat flux attenuation.

The clothing on the mannequin were exposed repeatedly to heat flux levels higher than 5 kW/m^2 and one time to as high a level as 13 kW/m^2 for over 20 seconds[4]. In none of these instances did the clothing show any type of degradation nor was there any ignition, even though the outer clothing of the male mannequin was a black, full sleeve, 65% polyester shirt. Only the hair on the mannequin head was singed. Hence, it can be categorically stated that under conditions of 5 kW/m^2 heat flux exposure levels there is absolutely no cause for concern with clothing ignition.

Other effects noticed in these tests include the dependence of the AF on the magnitude of the heat flux and on the tightness with which the outer and inner shirts are held together. It was found that the tighter the clothing the lower was the AF. Similarly, the higher the heat flux the lower was the AF, all other conditions being similar. However, no systematic study of these parameter variations was undertaken to provide any quantitative correlation.

One of the real effects of exposure of a human being to radiant heat flux is the generation of body sweat, which will tend to wet the clothing. In this series of tests the effect of clothing wetness on the AF was not studied. It can be however, surmised that the presence of wetness of clothing will only increase the value of AF by the clothing moisture absorbing the water vapor band energy in the incident IR beam. Secondly, the evaporation of the water from the clothing will absorb considerable energy thereby increasing the effective absorptivity of the garment (hence, higher AF than in dry clothing). What is uncertain is the effect of steam thus generated. Whether this steam will cause its own burns on the person's skin is uncertain and should be subject of a future research. One can, perhaps, postulate that the steam will be generated a relatively low temperature (35 ^oC to 40 ^oC) and hence may not present a problem - only definitive tests can provide answers.

Finding # 2: Any object that intervenes between the heat flux source and the object receiving the heat flux results in a substantial decrease in the heat flux to the object. The object could be as thin as a single sheet of newspaper.

The test results obtained by placing a single (and double sheets) of a newspaper in front of the radiometer are very revealing. A single sheet of newspaper (of thickness 0.076 mm or 3 x 10^{-3} inch) held about 5 cm from the object results in an attenuation factor of about 5 at heat flux levels of 5 kW/m^2. This attenuation is far larger than those from the clothing (even with thickness 3 to 4 times that of the newspaper). The complete scientific reason for this level of attenuation is not clear. It is possible that the distance between the radiometer and the newspaper has significant effect (involving the back scatter of IR radiation by the newspaper). In the case of clothing, the "inside" radiometer was essentially at the back surface of the inner shirt and therefore, collected all of the back scatter energy – resulting in lower AF values.

The results with newspapers also indicate that both the thickness of the newssheet and the magnitude of the incident IR radiation have significant impact on the attenuation factor. A more systematic study of this intriguing result should be made. Also not measured (or maintained) in

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[4] This occurred because at the end of one of the tests the firemen directed a water stream on to the burning pool of LNG, as a part of the firemen training. This resulted in RPTs and the formation of a very large fireball, which essentially was over the mannequins (that had not been removed from their locations) as an umbrella of fire. The radiometers did record very high levels of heat flux.

these tests was the moisture content of the newssheet. Paper, a cellulosic material, contains moisture, which depends on the relative humidity in the atmosphere. Moisture in the object will have strong effect on energy absorption. Finally, not investigated in this series of tests are the temporal variations in the attenuation factor (due to possible demoisturization of the paper) of a newssheet with long-term exposure to the same level of incident radiation. It was not possible in this series of tests to maintain a steady level of incident heat flux, thanks to the wind driven movements of the fire.

Finding # 3: At 4 kW/m^2 radiant heat flux level a person can be exposed for as long as 60 to 120 seconds without feeling either severe pain or suffering any skin burns. At 5 kW/m^2 a person can withstand the heat flux without much pain or permanent injury or skin burns for 25 to 30 s.

The values for heat flux and the duration of exposure without pain or injury have some ranges because of the nature of the tests. The author ("human subject") repeatedly exposed himself in the course of a single fire burn trial without much cooling after each data taking episodes. This diminished the duration of time that he could withstand the same heat flux because of the higher temperature of his clothing as well as of the exposed skin. The longer duration number presented above, therefore, must be associated with the first time a person is exposed to the fire without any prior exposures to the same level of heat fluxes.

The results from these full body human exposure tests prove that the public safety criterion enshrined in regulations and LNG standards, based on a 5 kW/m^2 radiant heat flux exposure for 30 seconds, is a very conservative. Medical literature is replete with results from small laboratory scale experiments, which predict that a human skin exposed to 5 kW/m^2 for 30 seconds and at 4 kW/m^2 for 40 seconds will result in severe 2nd degree burns. No such results were found in the full body, live human, tests conducted in these series of experiments. In none of the tests with exposure times measured in several tens of seconds (up to 120 seconds) did the author feel any severe pain, temporary or permanent injury or any skin burns. The results from the current series of tests, therefore, clearly indicate the effect of the resilience of the human body to react to heat exposure and act a system rather than as a single small (dead) skin specimen used in the laboratory tests. In effect, the current standards are overly conservative even for the exposure of the bare skin.

As has been shown with other data from the clothing protection and obstruction effects, the realistic exposure radiant heat flux actually incident on the skin of a normally clothed human being in an urban or industrial environment when the calculated nominal heat flux level at his location is 5 kW/m^2 will be much smaller, perhaps, of the order of 2 kW/m^2 or 3 kW/m^2. At this level of radiant heat flux one does not feel even a discomfort, let alone suffer a skin burn. Therefore, the proposals that some have championed in public hearings to reduce the statutory safety level of 5 kW/m^2 to 1.6 kW/m^2 are scientifically unsupportable and baseless.

Finding # 4: The temperature measured on the skin of a fiberglass mannequin exposed to radiant heat does not provide a representation of the temperature attained by the skin of living human being.

This is because, when a mannequin and human being are exposed to the same levels of incident radiant heat, their reactions are completely different. The heat flux that goes through the clothing of the mannequin tends to heat up the mannequin skin locally to high temperatures due to the fact that the mannequin body is made of non conducting fiberglass and all heat incident locally is utilized to increases the skin temperature. This is in stark contrast to the reaction of a human being; when heat flux reaches the skin and as the skin temperature begins to rise an increased blood flow results locally to carry away the heat. Secondly, the body sweats significantly (as was experienced by the author) resulting in the evaporative cooling of the skin and maintenance of the normal body temperature. This is clearly illustrated in Figure 3-7. Hence, thermocouple data from mannequins should not be used to predict human skin temperatures.

4.2 Conclusions

1 The current criterion for public safety in the US regulations and standards (5 kW/m^2 for 30 s exposure) is very conservative, adequate and represents a very high level of factor of safety.

2 Very simple and even single layer clothing and other simple objects provide significant reduction in radiant heat flux to the skin of a person. The reduction in the heat flux levels by single layer clothing can amount to a factor of 2 or 3. Newspaper sheets in front of the face or hands can reduce the heat flux levels by factors of 5 or more.

3 Mannequins can be used as a substitute for live human tests to determine the effectiveness of clothing to reduce radiant heat flux to the skin. However, mannequins cannot as a substitute when determining the skin temperature rise due to exposure to a radiant heat flux, because the human physiology of skin cooling is completely and drastically different from that in a mannequin.

4 Because of the reduced area of the skin exposed to the fire in a clothed person, the human physiological systems may work to reduce the effect of the heat flux on the exposed part of the skin by carrying away heat and initiating the sweating protective mechanism. That is a partially clothed human body may withstand a higher heat flux exposure than a completely naked body.

4.3 Recommendations

In the tests conducted not all parameters that could have been varied were actually varied or when varied the range of variation was limited. Some of the parameters will have significant influence on the results and need to be used in future tests. With this in mind the following recommendations are made for future research.

1 Tests should be conducted with mannequins protected from fire during the periods when no data are recorded. This will ensure that conditions that prevail in a sudden and unexpected exposure of a person to LNG fire (in an accident scenario) can be duplicated properly.

2 Human subject, if used, must be able to “cool off” or completely protected from fire exposure (however small) before initiating additional data gathering trials.

3 Tests with hand held radiometer or strapped on radiometer must be designed such that the instruments are capable of relaying the data captured by wireless to the computer at rates exceeding 10 Hz. Wiring limits the ability of the person to ambulate to maintain the same heat flux level. Wiring also limits the ability to move the mannequins quickly.

4 Future tests should be designed to move the mannequins easily (located on wheeled trolleys) so that their location with respect to the fire can be changed quickly and easily.

5 Experiments similar to the ones conducted in this series need to be carried out with bigger LNG fires for the following reasons. In a larger LNG fire,

- The distribution of radiant energy as a function of the spectral wavelength will be different compared to that in a smaller fire due to soot effects in larger fires.

- The distance to 5 kW/m^2 heat flux location will be larger. Because of the larger distance, the absorption of the IR in the atmospheric water vapor and CO_2 bands will be higher and could be significant. This may influence the ability of a person to withstand an overall heat flux of 5 kW/m^2 for longer duration because the spectrum of energy incident on the skin will be devoid of energy in the water vapor and CO_2 bands.

- A given wind speed has smaller effect on larger fires than on smaller diameter fires. Therefore in a larger fire, a given wind speed will produce less variations in fire plume tilt and, consequently, more steady incident heat flux.

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Appendix A

Specifications, Calibrations and Other Details of Instruments

A-1 Wide-angle Radiometers

In each test two units of three types of wide-angle radiometers manufactured by MidTherm Corporation were used. These were (i) the infrared radiometer [model #32R (ZnSe)-1-0-394-21325A], (ii) heat flux transducer [model # 32F-1-394-21037] and heat flux transducer [model # 24-1-21581]. All of these radiometers are of the natural cooled type and, therefore, required no special cooling accessories to function in a field environment. These wide-angle radiometers had a range of 0 to 12 kW/m^2. Exposure to a heat flux greater than the maximum specified require the instruments to be cooled to give accurate readings.

Figure A-1 shows the manufacturer drawing with the dimensions and other information for the infrared radiometer [model #32R (ZnSe)-1-0-394-21325A]. This radiometer was fitted with a Zinc-Selenium (ZnSe) window of thickness 1 mm. The calibration chart (supplied by the manufacturer) of voltage produced vs. exposure heat flux, for the model 21325A infrared radiometer fitted with the ZnSe window is presented in Figure A-2. Figure A-3 indicates the transmissivity of the ZnSe window as a function of the wavelength of radiation. It is known from other LNG fire experiments that the wavelength region of 1 μm to 10 μm (the near IR region) contains most of the energy radiated by a large LNG fire.

Figure A-4 shows the details of the heat flux transducer [model # 32F-1-394-21037, another type of radiometer]. The calibration chart (relationship between the voltage developed vs. the incident heat flux) for this heat flux transducer is shown in Figure A-5.

Figure A-6 shows the details of the heat flux transducer #21581 and its calibration chart is shown in Figure A-7. Unfortunately, these radiometers did not properly record the heat fluxes because they were not mounted on a plate (as they were supposed to have been).

A-2 Hand-held Infrared Radiometer

In addition to using the two types of radiometers described above a hand-held, wide angle, portable radiometer was also used. Figure A-8 shows a photograph of this radiometer. The radiometer wand is 15 cm long and 5 cm diameter at the front; however, the heat flux sensing element is only 1 cm in diameter and is located at the front end of the wand. The radiometer is connected by a cable to a hand-held read out meter, which displays the magnitude of the heat flux on the window. The particular unit used in the tests was factory calibrated to read out the heat flux levels in W/m^2 (0 – 10,000). Other relevant specification information for this radiometer is included in Figure A-9.

This radiometer integrates the incoming flux at 0.1 s intervals and displays the mean value over this interval. The radiometer can also be connected to a computer through a serial port (on the readout unit) for digital recording of the data. Unfortunately, because of the (inflexible) sampling program that was included with this model, the data could be stored only in 10 s intervals (i.e., the data averaged over 10 s and the mean of the data values over this period is stored, every tenth second).

A-3 Thermocouples

Air immersion thermocouples were used to measure the temperature of the air near the mannequins, temperature just in front of the outer layer of clothing, and behind the inner clothing (between the skin of the mannequins and the inner clothing). The thermocouples used were of type J, air/immersion bare tip probe type. The beads were of 1/16" diameter, with temperature measurement range of 32 ^{o}F to +1400 ^{o}F with a response time of 0.3 seconds. Each thermocouple wire terminated in a mini connector which was connected to a data logger.

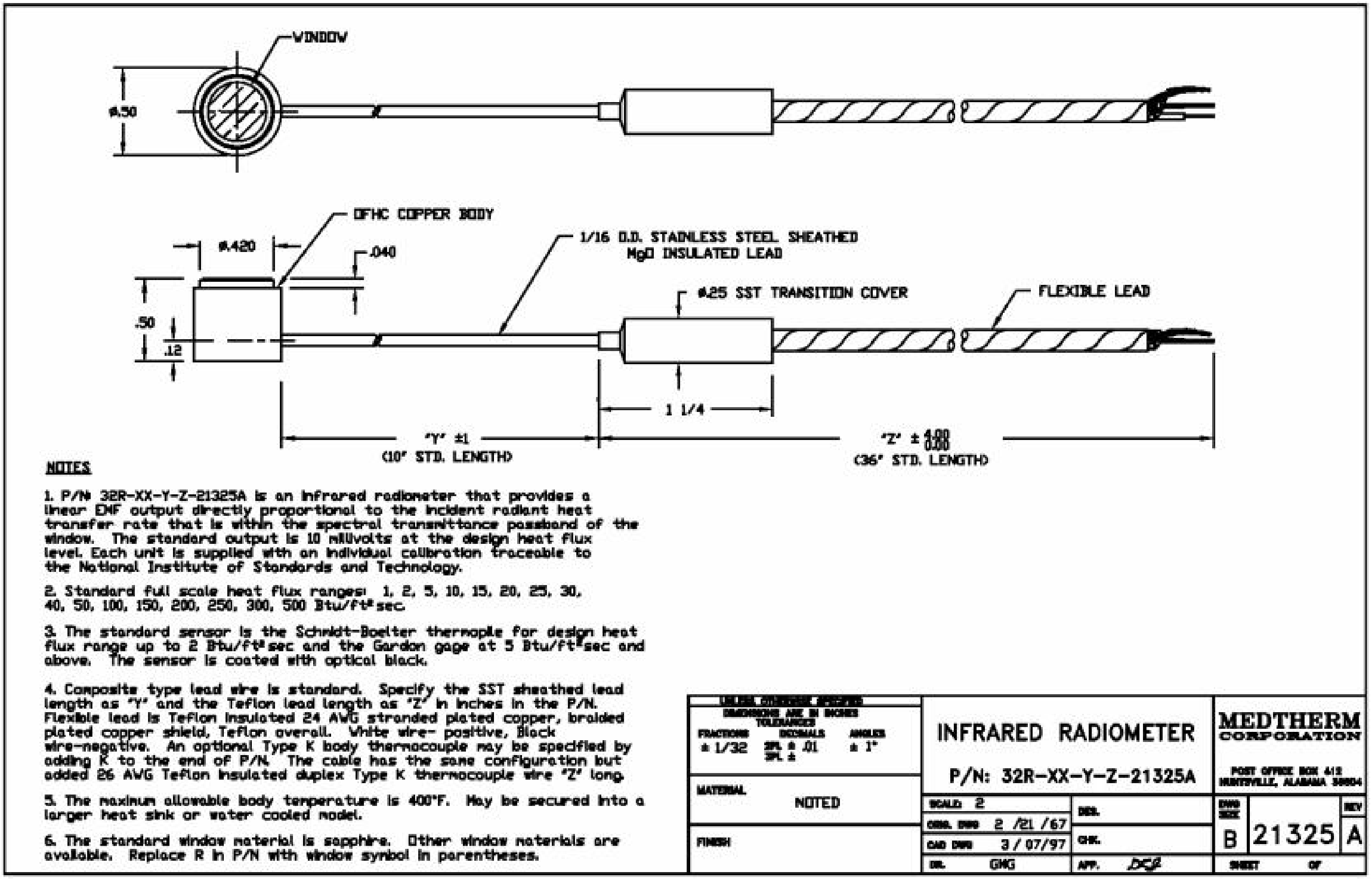
A-4 Meteorological Data

The Vantage Pro2™ Plus weather station manufactured by Davis Instruments of Hayward, CA was used to gather the wind speed, wind direction, atmospheric temperature and relative humidity data during the experiments. This weather station was located at some distance (about 100 ft) from the center of the fire so that any micro-meteorological effects created by the fire did not influence the atmospheric data gathered by the instrument.

The weather instrument consists of an anemometer, a thermocouple station, a rain collector and a humidity gage and a fan aspirated radiation shield. These instruments are mounted on a tripod at a height of about 2 m from the ground. The data collected by the instruments is downloaded through a wireless link to a Vantage Pro2™ Console. A rechargeable battery, charged by a solar panel, powers the weather instruments. Figure A-10 and Figure A-11 show, respectively, the weather station mounted on a tripod and the data-logging console. The data collected and stored in the console are later downloaded into a laptop computer using the "Weatherlink" data logger & software for Vantage Pro2™. The weather data were taken at 1 min intervals and stored on the laptop.

A-5 Other Data Collecting Instruments

The data from the thermocouples and the radiometers were fed to a National Instrument Data Acquisition and Control Module (Model # NI-SCXI-1600). Figure A-12 shows a photograph of this instrument. The input into the module is through 32-channel, milliVolt signal amplifier (Model # NI-SCXI-1102), which mates with the Channel Isothermal Terminal Block (Model # NI-SCXI-1303). The data acquisition module (DAQ) receives the input milliVolt DC signals, conditions and digitizes the signals. These data together with internal clock generated time data are fed to a laptop computer through a USB port. The digital data are stored and displayed using the LabVIEW™ software system developed by National Instruments. This software tool is used in the industry for design development, control and testing of data systems. The system provides built-in I/O and interactive user interface controls for data acquisition, manipulation, display and plotting as well as active control of the equipment based on the value of the data.



Source: Medtherm Corporation

Figure A-1: Specification drawing for the MedTherm Infrared Radiometer

CERTIFICATE OF CALIBRATION

DATE 8/30/06
CUSTOMER TMS
Burlington, MA
P.O. NO. 2006-01-145
CERTIFICATE NO. 14653-5
MODEL NO. 32R(ZnSe)-1-0-394-21325A
SERIAL NO. 146535
SENSOR TYPE Schmidt-Boelter
ABSORPTANCE 0.94
WINDOW Zinc Selenide
REFERENCE STANDARD 587025A
CALIBRATED BY 6

CALIBRATION RESULTS SUMMARY:

FULL SCALE OUTPUT LEVEL:
10.91 mV at 10 kW/m2

RESPONSIVITY:
1.091 mV per (kW/m2), or
the inverse: 0.9166 (kW/m2) per mV

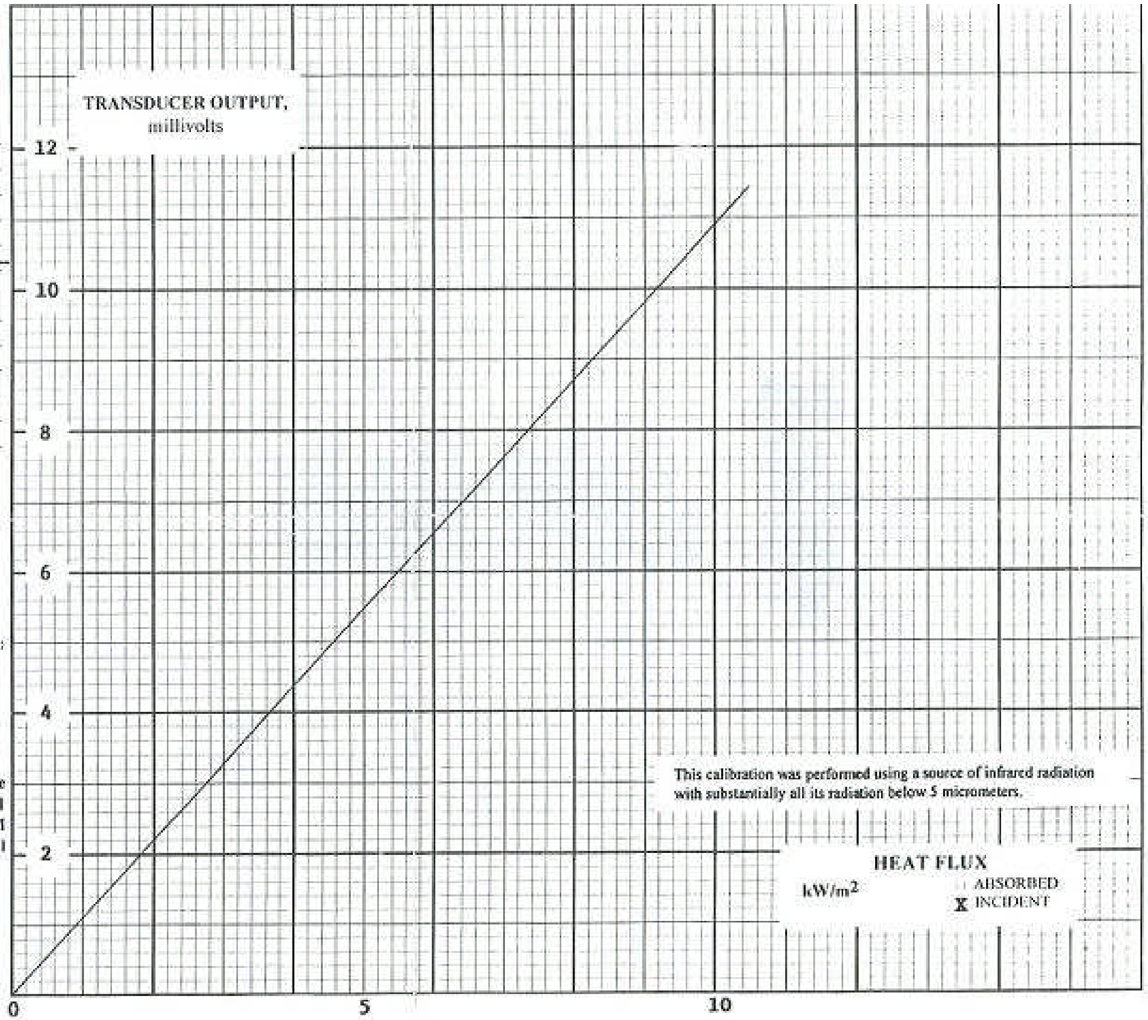
UNLESS NOTED, CALIBRATION CONDITIONS:
Non-condensing Ambient Air at 23 ±3 °C
Relative Humidity Less Than 70%
Expanded uncertainty ±3% of responsivity.
Coverage factor k=2, ~95% confidence level.
Test uncertainty ratio (TUR) is less than 4:1.

Calibration was performed in compliance with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A to MEDTHERM PI-20 with traceability to the National Institute of Standards and Technology.

This certificate applies only to the item described above. It is not to be reproduced, except in its entirety, without written permission from MEDTHERM Corporation.

ATTEST: F. Beckett

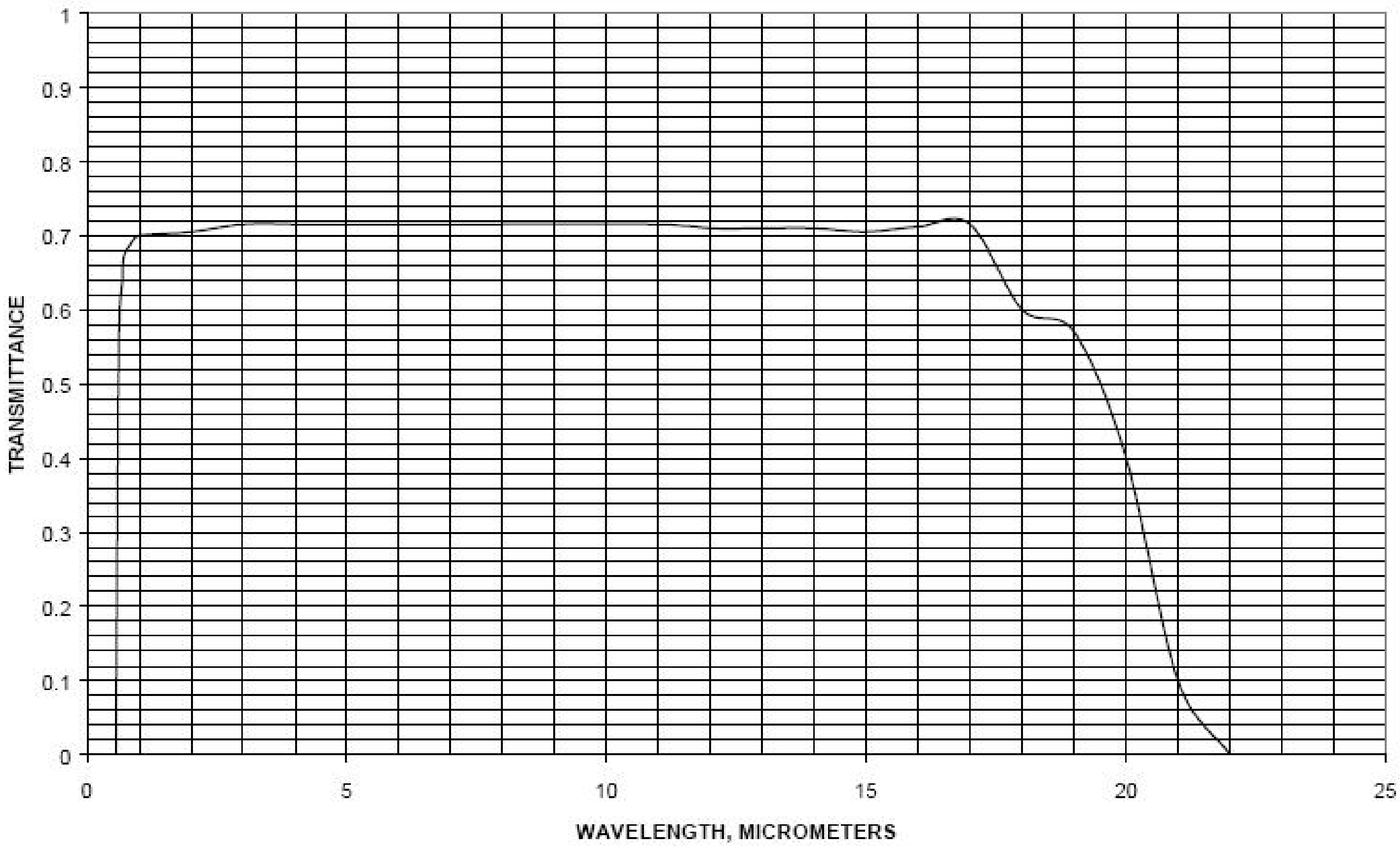
X QA Manager ___ President



MEDTHERM CORPORATION

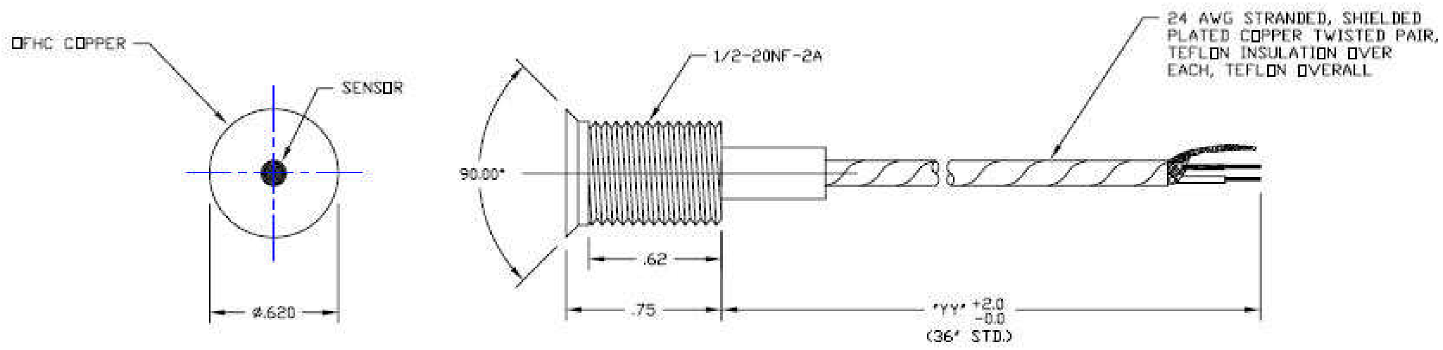
POST OFFICE BOX 412 / HUNTSVILLE, ALABAMA / TELEPHONE (256) 837-2000 / FAX (256) 837-2001

Figure A-2: Calibration chart (w. ZnSe window on) for the MedTherm Infrared Radiometer, 21325A



Source: Medtherm Corporation

Figure A-3: Transmission characteristics of 1 mm thick ZnSe window on the transducer



NOTES:

1. P/N: 32F-XX-YY-21037 is a total heat flux transducer which provides a linear EMF output directly proportional to the net absorbed heat transfer rate to the sensing tip. The standard output is 10 millivolts at the design heat flux level "XX" in Btu/ft²sec. Each unit is supplied with an individual calibration traceable to the National Institute of Standards and Technology.

2. Standard ranges: 0.2, 0.5, 1, 2, 5, 10, 15, 20, 25, 30, 40, 50, 100, 150, 200, 250, 300, 500, 1000 Btu/ft²sec

3. Standard sensor is Schmidt-Boelter thermopile for design heat flux range up to 40 Btu/ft²sec and Gardon gage at 50 Btu/ft²sec and above. Sensor coated with optical black.

4. Lead wire is 24 AWG stranded copper with Teflon insulation over each wire, Teflon jacket overall. (White wire positive, Black wire negative)

5. Thin brass hex jam nut (P/N: N-21037, 3/4 hex X .167 thk) is available if desired for mounting.

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES
FRACTIONS ± 1/32 | DECIMALS 2PL ± .01, 3PL ± .005 | ANGLES ± 1°

MATERIAL: NOTED

FINISH

HEAT FLUX TRANSDUCER

P/N: 32F-XX-YY-21037

SCALE: 2		DES.	
ORIG. DWG	3 /21 /67		
CAD DWG	12/18 /92	CHK.	
DR.	GMG	APP.	DCD

MEDTHERM CORPORATION
POST OFFICE BOX 412
HUNTSVILLE, ALABAMA 35804

DWG SIZE: B | 21037 | REV
SHEET | OF

Source: Medtherm Corporation

Figure A-4: Specification drawing for the MedTherm Heat Flux Transducer 21037

CERTIFICATE OF CALIBRATION

DATE 8/29/06
CUSTOMER TMS
Burlington, MA
P.O. NO. 2006-01-145
CERTIFICATE NO. 14653-3
MODEL NO. 32F-1-394-21037

SERIAL NO. 146533
SENSOR TYPE Schmidt-Boelter
ABSORPTANCE 0.94
WINDOW None
REFERENCE STANDARD 587025A
CALIBRATED BY 6
CALIBRATION RESULTS SUMMARY:
FULL SCALE OUTPUT LEVEL:
9.97 mV at 10 kW/m^2
RESPONSIVITY:
0.997 mV per (kW/m^2), or
the inverse: 1.003 (kW/m^2) per mV

UNLESS NOTED, CALIBRATION CONDITIONS:
Non-condensing Ambient Air at 23 ±3 °C
Relative Humidity Less Than 70%
Expanded uncertainty ±3% of responsivity.
Coverage factor k=2, ~95% confidence level.
Test uncertainty ratio (TUR) is less than 4:1.

Calibration was performed in compliance with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A to MEDTHERM PI-20 with traceability to the National Institute of Standards and Technology.

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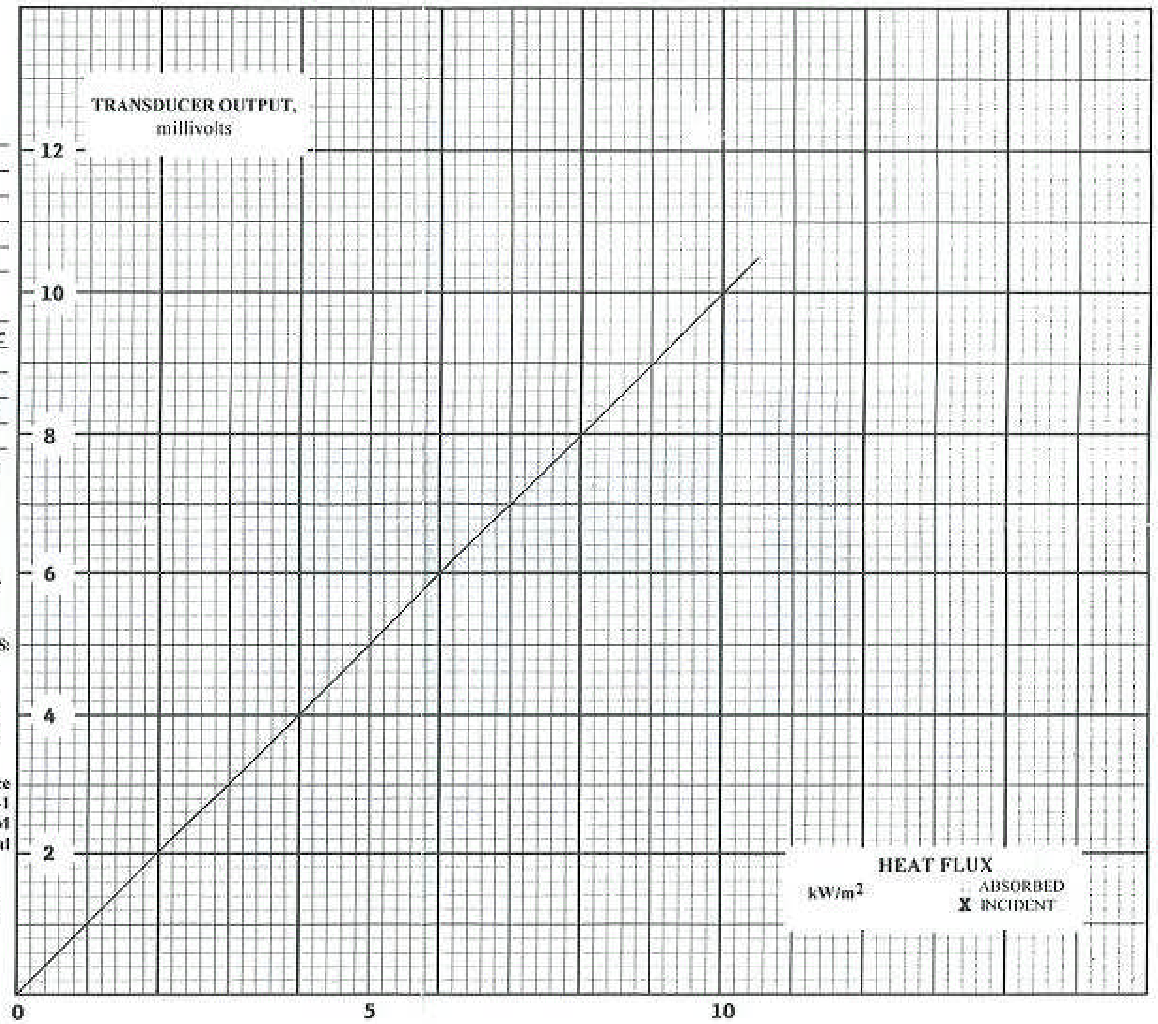
ATTEST: F. Beckett

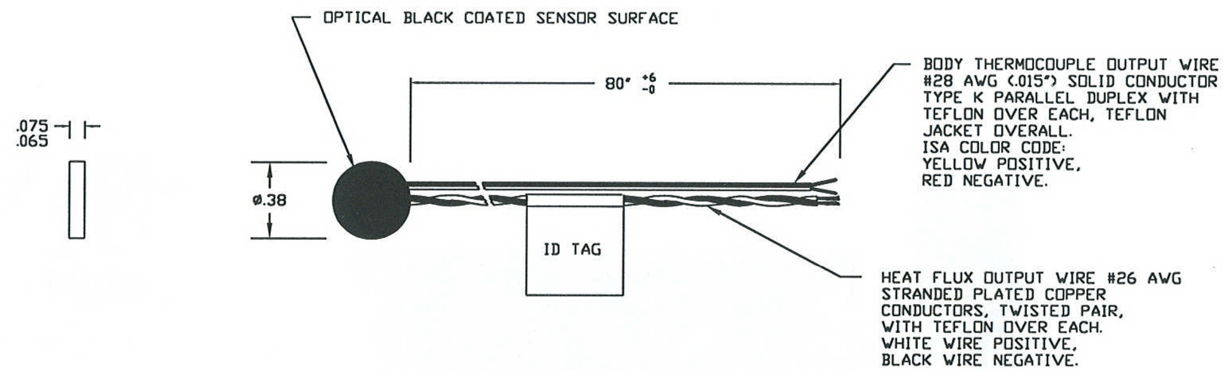
X QA Manager ___ President



MEDTHERM CORPORATION

POST OFFICE BOX 412 / HUNTSVILLE, ALABAMA / TELEPHONE (256) 837-2000 / FAX (256) 837-2001

Figure A-5: Calibration chart (no window) for the MedTherm Heat Flux Transducer, 21037



NOTES:

1. P/N 24-1-21581 is a total heat flux transducer that provides a linear EMF output directly proportional to the net absorbed heat transfer rate to the sensor. The standard nominal output is 12 millivolts at the design heat flux level of 1 Btu/ft²sec. Each unit is supplied with an individual calibration traceable to the National Institute of Standards and Technology.

2. The heat flux sensor is a MEDTHERM Schmidt-Boelter thermopile with range from 0 to 1 Btu/ft²sec. The sensor face is coated with optical black. The body thermocouple is Type K. The maximum allowable body temperature is 250°C.

3. The heat flux output wire is #26 AWG stranded plated copper conductors, twisted pair, with Teflon over each. White wire-positive, black wire-negative. The thermocouple output wire is #28 AWG parallel duplex with Teflon over each, Teflon jacket overall. The wire is the standard ISA color code of positive wire yellow and the negative wire red. The standard leadwire length is 80 inches.

4. The body material is aluminum alloy, anodized per MIL-A-8625C, Type III, Class I. The body has high thermal conductance and low thermal mass and is designed for bonding with low thermal resistance on the surface, or into a recess in the surface, of the object of measurement interest.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES FRACTIONS ±.25 DECIMALS 2PL ±.02 3PL ±.010 ANGLES ±30'	HEAT FLUX TRANSDUCER P/N: 24-1-21581	MEDTHERM CORPORATION POST OFFICE BOX 412 HUNTSVILLE, ALABAMA 35804
MATERIAL NOTED	SCALE: / ORIG. DWG 3/21/78 / CAD DWG 7/08/00 / DR. GMG — DES. / CHK. / APP. DEJ	DWG SIZE B 21581 REV
FINISH		SHEET OF

Figure A-6: Specification drawing for the MedTherm Heat Flux Transducer 21581

CERTIFICATE
OF
CALIBRATION

DATE 8/29/06
CUSTOMER TMS
Burlington, MA
P.O. NO. 2006-01-145
CERTIFICATE NO. 14653-2
MODEL NO. 24-1-394-21581

SERIAL NO. 146532
SENSOR TYPE Schmidt-Boelter
ABSORPTANCE 0.94
WINDOW None
REFERENCE STANDARD 587025A
CALIBRATED BY 6
CALIBRATION RESULTS SUMMARY:
FULL SCALE OUTPUT LEVEL:
9.18 mV at 10 kW/m^2
RESPONSIVITY:
0.918 mV per (kW/m^2), or
the inverse: 1.089 (kW/m^2) per mV

UNLESS NOTED, CALIBRATION CONDITIONS:
Non-condensing Ambient Air at 23 ±3 °C
Relative Humidity Less Than 70%
Expanded uncertainty ±3% of responsivity.
Coverage factor k=2, ~95% confidence level.
Test uncertainty ratio (TUR) is less than 4:1.

Calibration was performed in compliance with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A to MEDTHERM PI-20 with traceability to the National Institute of Standards and Technology.

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ATTEST: F. Beckett

X QA Manager ___ President

MEDTHERM
CORPORATION

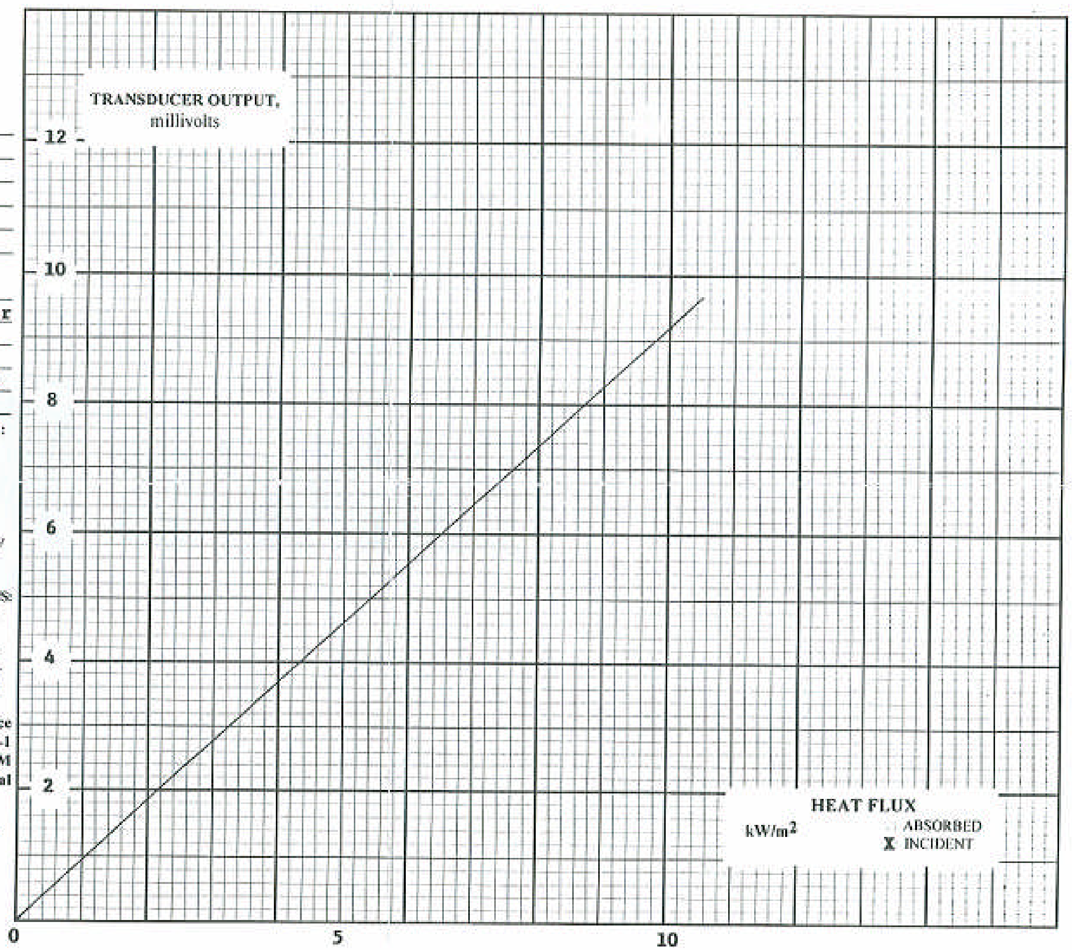


Figure A-7: Calibration chart (no window) for the MedTherm Heat Flux Transducer, 21581

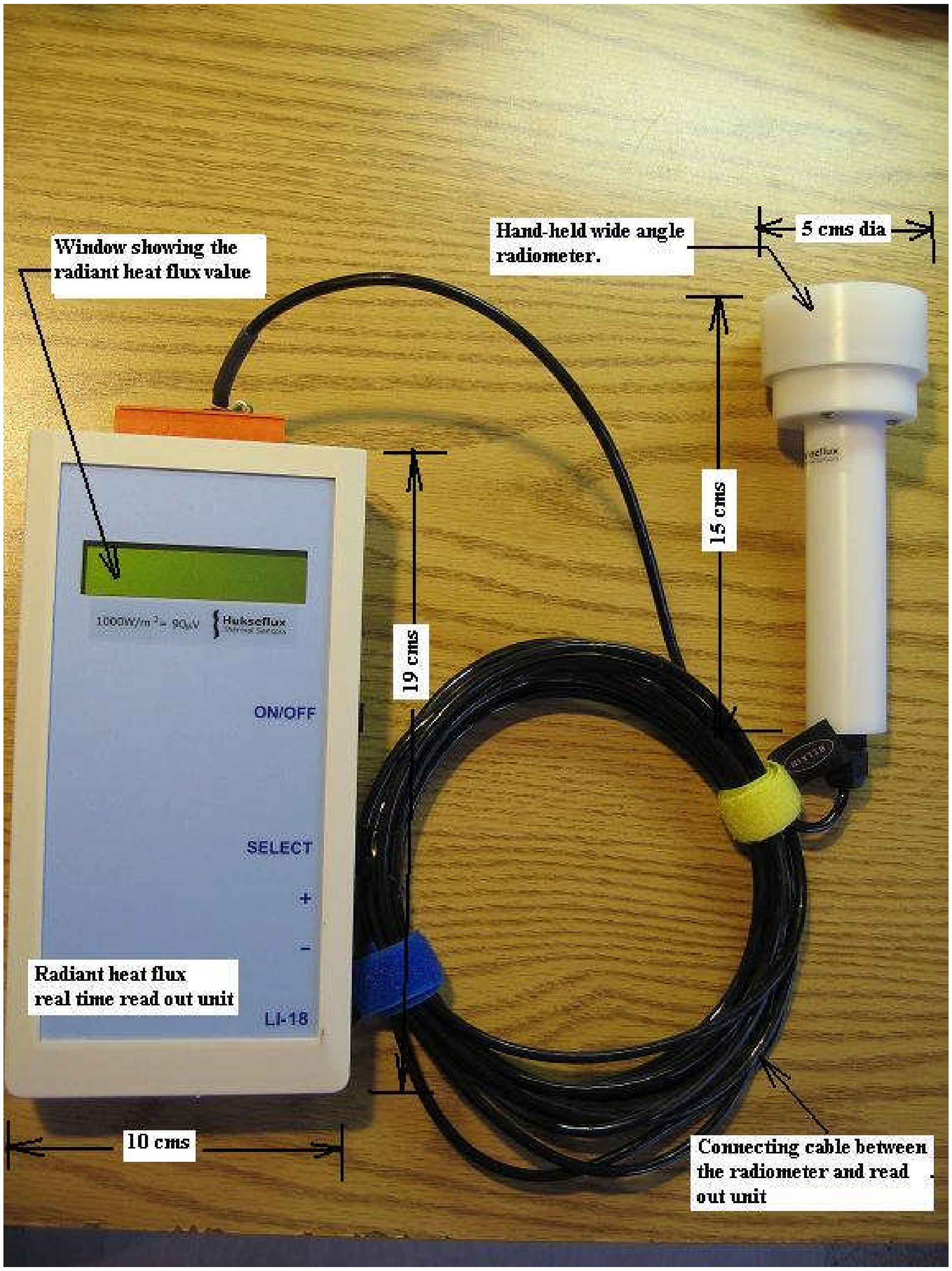


Figure A-8: Photograph of Hukseflux Thermal Sensor (hand-held radiometer), Model HF03

Hukseflux
Thermal Sensors

HF03 / LI18

HEAT FLUX SENSOR PORTABLE, WITH READ-OUT UNIT

The HF03 is a heat flux sensor that can be used in mobile applications. It is combined with LI18, a high accuracy hand-held read-out unit that can be used both for mobile measurements and as an amplifier directly connected to a PC.
The combination HF03 / LI18 is typically used to study heat flux levels around flares and fires, and to calibrate flare radiation monitors / flare heat flux sensors.

The HF03 is a heat flux sensor of the type that is commonly used in fire testing. The HF03 housing and sensor are designed such that they are suitable for short (10 minute) observation of high flux environments (up to 10 kW/m²)

LI18 is used to display the measured flux level; for attaining that, the sensitivity of HF03 is entered into the LI18 software, using the buttons on the side.
The LI18 is battery powered but also has a connection for a mains adapter that is typically used in indoor applications. An adapter (100-230 VAC - 50/60 Hz) is included in the delivery.

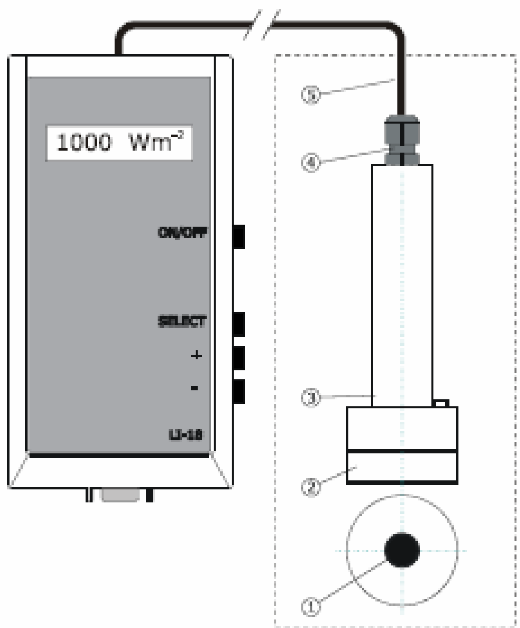


Figure 1 *LI18 connected to HF03. Heat flux sensor surface (1), metal heat sink (2), plastic grip (3), polyurethane cable (5).*

HF03 / LI18 SPECIFICATIONS

Heat flux range:	up to 10 kW/m²
Exposure time:	10 minutes (max)
Calibration traceability:	NIST
Cable length:	3 m
Display functions:	actual or integrated values set sensor type set calibration factor set internal clock read-out stored totals set integration method
A/D resolution:	1:10.000
A/D sample rate:	10/second
power supply:	standard 9V battery (PP3) or mains adapter 100-230 VAC

Figure A-9: General information and specifications of the hand-held radiometer, Hukseflux Thermal Sensor, Model HF03

As used during the tests

Manufacturer's photograph

Figure A-10: Vantage Pro2^{TM} weather station

Figure A-11: Vantage Pro2^{TM} weather data display console

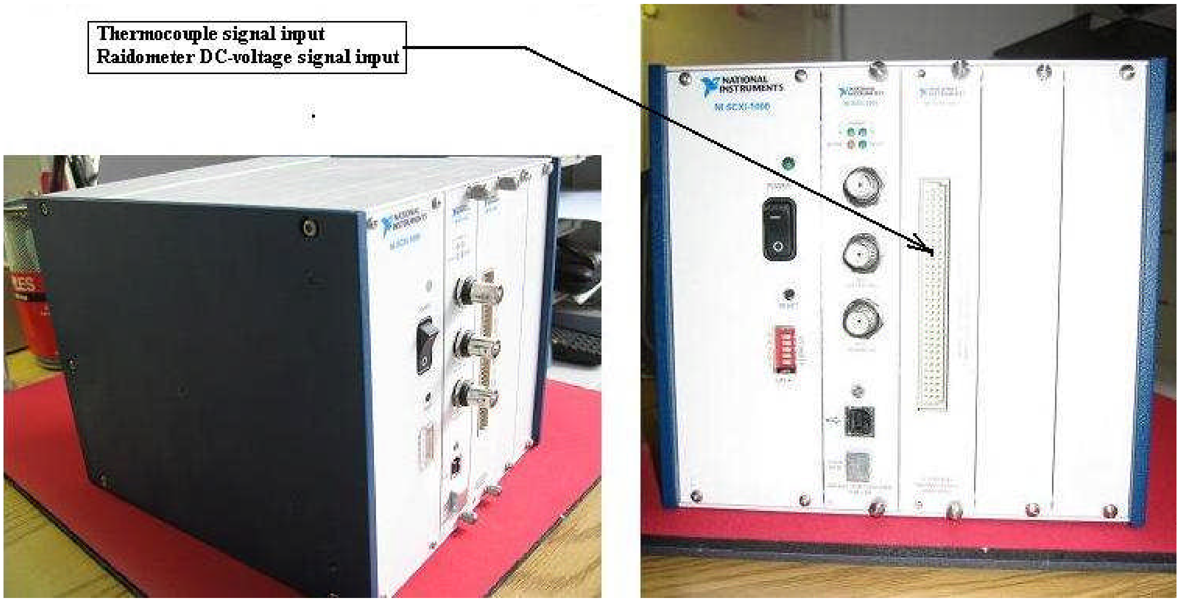


Figure A-12: Data Acquisition and Control Unit with thermocouple and radiometer signal input connector modules

Appendix B

Data from video films and other instruments

Table B-1: Data from the video film (of 9/28/06) on human exposure to radiant heat[(1)]

Session #	Measured Actual heat flux[(2)]	Clock on the video film	Duration of exposure	Distance[(3)] from dike edge	Distance[(3)] from dike center	Instantant flame height measured from film	Remarks
	kW/m^2	mm:ss	(s)	(ft)	(m)	(m)	
1	2.2	0:36:22		35	12.2	5.1	
		0:37:15	53	35	12.2	5.1	
2	4.4	0:37:53		21	7.9	3.0	Range of actual heat flux 3.8 to 5.8 kW/m^2
		0:37:59		21	7.9	5.1	
		0:38:16	23	21	7.9	4.6	Flame tilt w.r.t vertical about 30° away from observer
3	2.2	0:38:46		32	11.3	5.5	
		0:38:57		35	12.2	6.1	Heat flux was always > 2.7 kW/m^2
		0:38:59		35	12.2	4.9	
		0:40:08		31	11.0	4.3	>45° fire tilt away from observer
		0:40:10	84	31	11.0	4.9	
4	2.2	0:40:43		30	10.7	4.1	Flame low in height but fat
		0:40:50		31	11.0	7.1	Significant tilt away from observer
		0:41:35		31	11.0	8.1	Fire vertical (calm condition)
		0:42:22		31	11.0	4.1	
		0:42:26	103	31	11.0		
5	4.4	0:44:50		21	7.9	5.5	Vertical flame
		0:45:12	22	21	7.9		Wind shifted, flame towards observer
6	4.4	0:45:36		18	7.0	4.3	Approached the fire from a slightly different direction
		0:45:57	21	18	7.0		
7	2.2	0:46:59		25	9.1	6.1	Flame away from observer @ 20° tilt
		0:48:57		21	7.9	5.5	Heat flux > 3.1 kW/m^2. Flame away from observer @ 30° tilt
		0:48:59	120	21	7.9	5.5	Vertical fire

Notes: (1) Data recorded at about 2:00 PM; the sky was blue with scattered white cumulus clouds; the wind was somewhat gusty.

(2) The heat flux values identified in the audio part of the video film are incorrect due to hand-held radiometer calibration setting. The data in the table indicate the true radiant heat flux after correcting for the error.

(3) Distance marker traffic cones were set in this test (only) at 10 ft intervals to the east from the outer edge of the dike. The outer edge is 5 ft from the center of the dike. The data reported in the table are the distances from the dike center to conform to the norm in the fire radiation calculation literature.

Table B-2: Data on human exposure to radiant heat[1] from video film (of 10/05/06)

Session #	Measured Nominal heat flux[2]	Clock on the video film	Duration of exposure	Distance from dike center		Instantaneous flame height measured from film	Remarks
	kW/m^2	mm:ss	(s)	(ft)	(m)	(m)	
		0:01"39					Ignition of the fire
1	5	0:01:50		32	9.8		Half sleeve, white shirt and washed blue jeans worn.
		0:02:02		30	9.1	7.5	
		0:02:06		30	9.1	6.8	
		0:02:18	**26**				Fire slightly brick red
2	5	0:10:28				6.1	LNG pool ignition. Flames high
		0:10:38		38	11.6		Raj walks towards fire
		0:10:47		35	10.7	5.5	Fire bright yellow
		0:10:51		35	10.7	9.1	Very tall fire
		0:11:00		32	9.8	5.5	Fire bright yellow
		0:11:06		37	11.3		Quite tall flames.
		0:11:10	**42**	40	12.2		Quit exposure
3	5	0:13:43		30	9.1		Fire getting much redder
		0:13:59		28	8.5	5.5	Go closer because fire is diminishing is height. Also very brick red in color
		0:14:07	**24**	28	8.5		Quit exposure

Notes: (1) Data recorded at about 1:30 PM; the sky was partly cloudy at the beginning of the test. However, towards the end of the test (about 15 minutes) the sky became quite gray with clouds. Initially the wind was very light. Towards the end the wind was in the 5 – 10 kph range and constantly shifting in direction.

(2) Heat flux measured by the hand-held radiometer was in the 4.9 – 6.2 kW/m^2 range

Table B-3: Data on human exposure to radiant heat[(1)] from video film (of 11/02/06)

Session #	Clock on the video film (mm:ss)	Duration of exposure (s)	Distance from dike center (ft)	(m)	Instantaneous flame height measured from film (m)	Remarks
1	01:20		32	9.8	5.1	Raj w. full sleeve shirt and washed blue jeans worn. Fire ignition time. Fire tilted 30^o to east
	01:29		30	9.1	7.0	Raj begins to walk toward the fire
	01:39		32	9.8	7.0	Flame drag spill over downwind . Bright yellow fire
	02:00		28	8.5	7.0	
	02:04		34	10.4		Fire tilts towards Raj
	02:11		34	10.4	7.3	30^o to 40^o bend of fire towards Raj
	02:17	**57**				Walk away from the fire
2	02:42				4.9	Begin walking towards fire from 40 ft
	02:45		30	9.1	4.9	Fire low but fat and bushy at the bottom
	02:46		32	9.8	5.2	Very bushy fire (showing the formation of a vortex ball combustion at the base)
	02:58	**16**	30	9.1	5.0	Stop and back off from fire
3	03:02		28	8.5	4.6	
	03:15		29	8.8	4.8	
	03:22		25	7.6	5.3	Flame bent 60^o or more to east
	03:34	**32**	28	8.5	5.7	Flame very tall and brick red. Very tilted fire plume.
4	04:08		25		5.0	Flame very yellow- highly bent
	04:24		28	8.5	-	
	04:26		30	9.1	5.0	Bright yellow fire (very large diameter at the bottom with fireball vortex)
	04:28	**20**				Back off from fire
5	06:45		30	9.1	2.4	Very low height fire – completely dragging on the east side due to wind
	07:06	**31**	30	9.1	7.0	Very tall fire plume – brick red in color.

Notes: (1) Data recorded at about 1:20 PM; the sky was partly cloudy at the beginning of the test but became quite sunny by the middle of the test. However, it was blustery with quite high shifting direction winds (10– 15 kph range). Approach of the fire was from the west.

Heat flux measured by the hand-held radiometer to locate the person as close as was possible to 5 kW/m^2. Digital data on the heat flux received were measured by two Medtherm radiometers attached to the person, only from session 7(in the above table) and afterwards.

Table B-3 (cont'd)

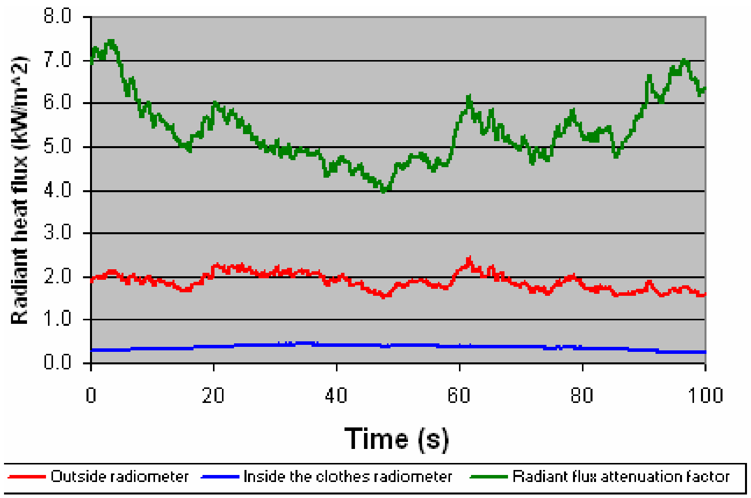
Session #	Clock on the video film (mm:ss)	Duration of exposure (s)	Distance from dike center (ft)	(m)	Instantaneous flame height measured from film (m)	Remarks
6	10:52		30		4.1	Flame brick red in color. Considerable drag of the flames on the downwind side throughout this session.
	10:59		25		4.3	During all of this session the hand held radiometer was reading 4.5 to 6 kW/m^2
	11:18				4.1	
	11:30	**38**			4.5	Walk back away from fire
	14:49	**--**	--	--	-----	**Fire Extinguished**
Heat Flux digital data recorded from two Medtherm radiometers affixed to Raj in sessions 7 and beyond						
7	15:00					Raj walks towards the fire. Hand held radiometer indicates 5 kW/m^2
	15:50		30		5.1	
	16:04					Fire plume bends 45o towards Raj
	16:07	**17**	32		5.7	Fire fat in the middle, bright yellow-red
8	16:15		35			Vertical fire
	16:26		35		4.9	
	16:29		38			Fire bending away from Raj
	16:39		35			
	16:49		32			
	16:55		35			
	17:03	**48**	35		4.8	
9	17:14		37			Flame bending away from Raj@ 30^o
	17:33		37		5.2	Brick red flame – almost vertical
	17:35	**21**	Quit			

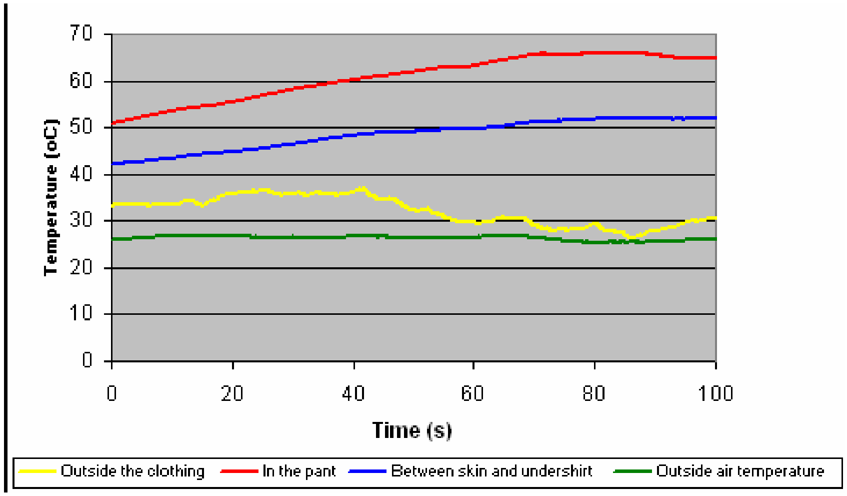
Appendix C

Plotted data on radiant heat fluxes and temperatures measured by instruments

C.1: Data from the clothed mannequin exposure tests

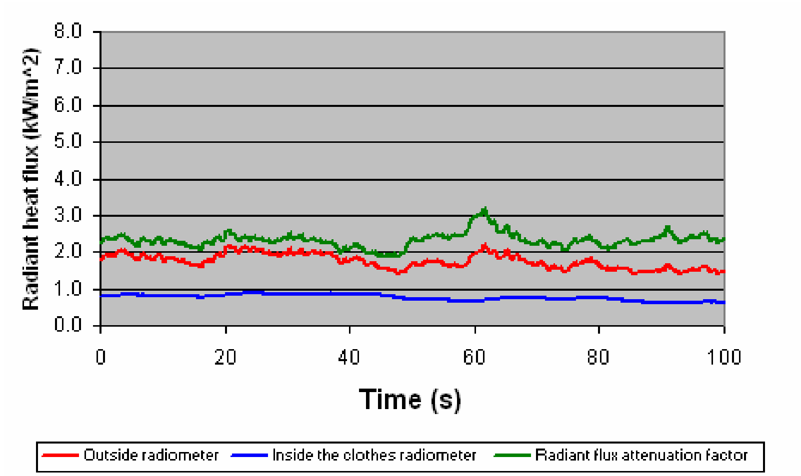
Test Date:	**09/28/2006**	Outer garment:	**White shirt**
Test #:	**1**	Inner garment:	**White undershirt**
Mannequin location:	**32 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin:	**Male**		
Radiometer view:	**Inner radiometer on the stomach**	Other Data:	None
	View through button flap on outer shirt		
	Double layer clothing		

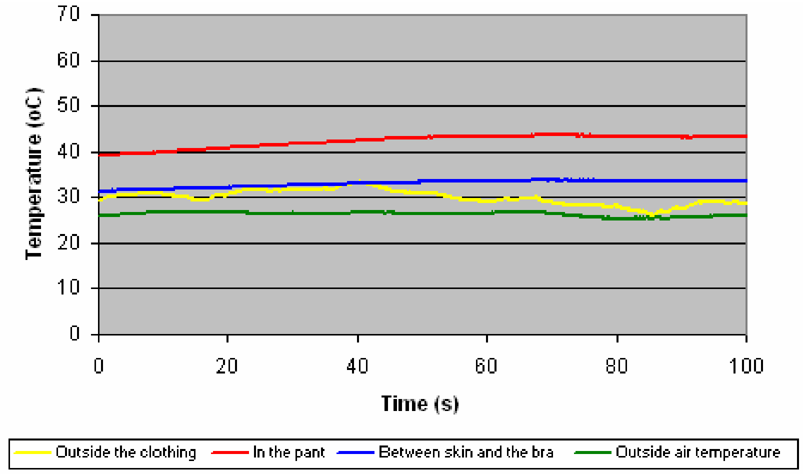




Test Date:	**09/28/2006**	Outer garment:	**Red shirt**
Test #:	**1**	Inner garment:	**Green undershirt**
Mannequin location:	**32 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin**:**	**Female**		
Radiometer view:	**Inner radiometer on the stomach View through stretched clothing**	Other Data:	None

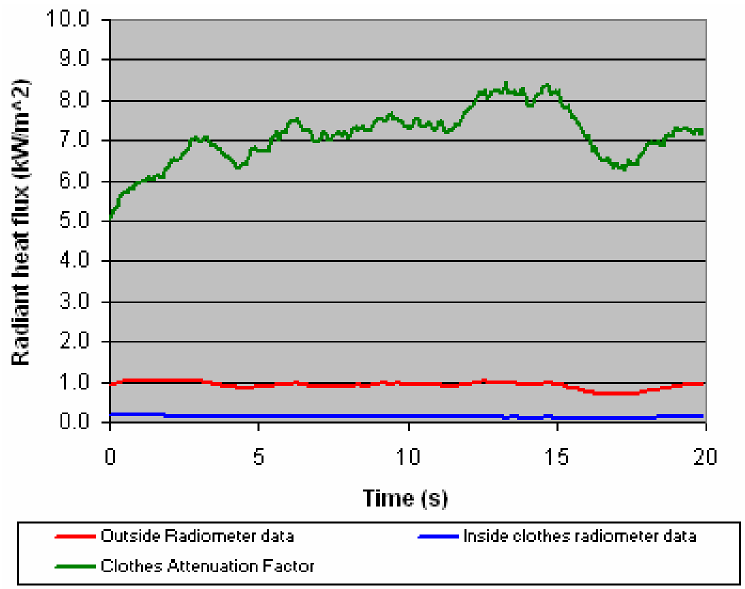
Double layer clothing

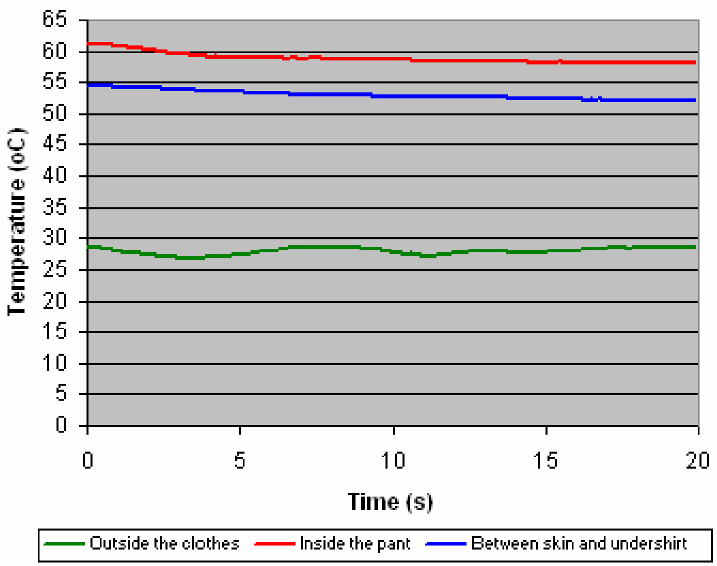




Test Date:	**09/28/2006**	Outer garment:	**White shirt**
Test #:	**2**	Inner garment:	**White undershirt**
Mannequin location:	**40 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin:	**Male**		
Radiometer view:	**Inner radiometer on the stomach** **View through button flap on outer shirt**	Other Data:	None

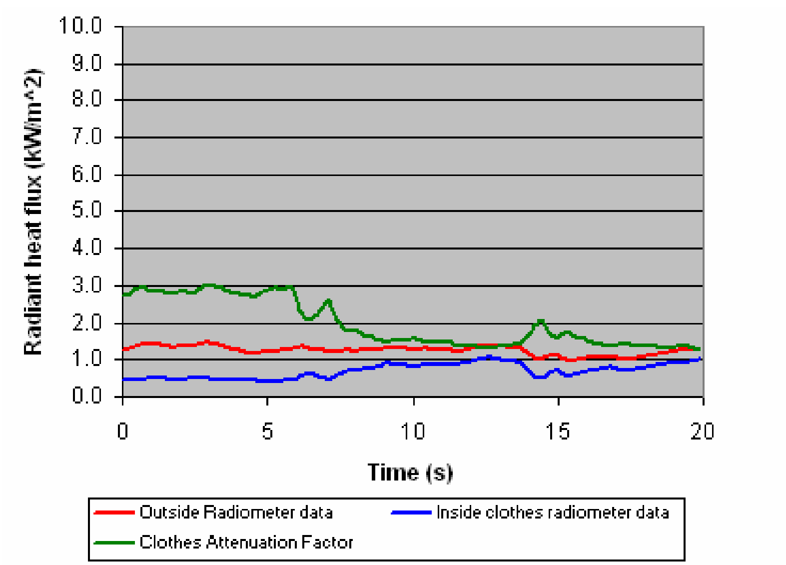
Double layer clothing

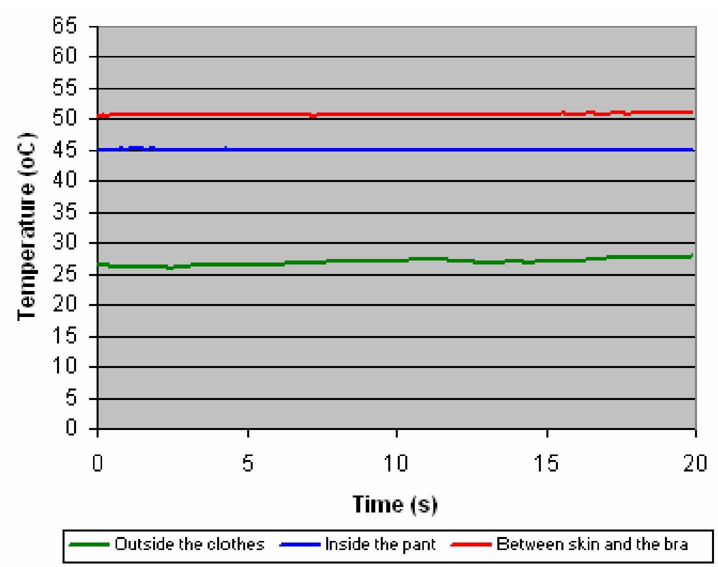




Test Date:	**09/28/2006**	Outer garment:	**Red shirt**
Test #:	**2**	Inner garment:	**Green undershirt**
Mannequin location:	**40 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin:	**Female**		
Radiometer view:	**Inner radiometer on the stomach** **View through stretched clothing**	Other Data:	None

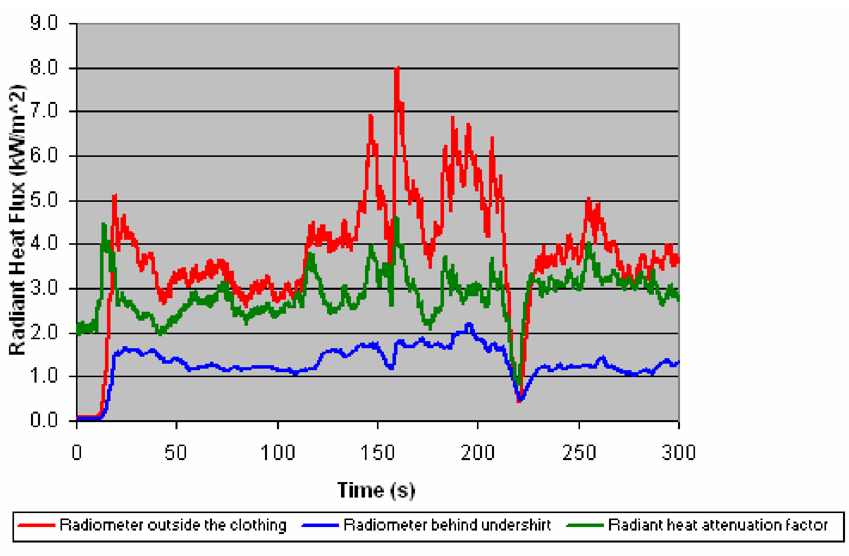
Double layer clothing

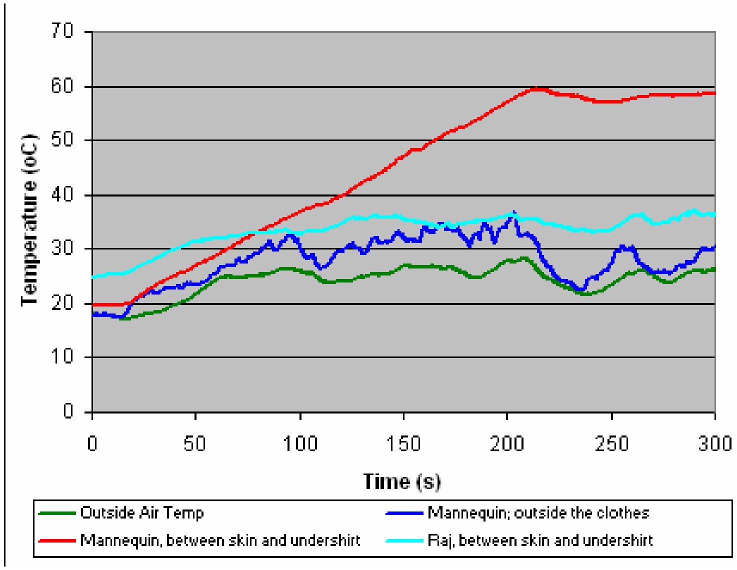




Test Date:	**10/05/2006**	Outer garment:	**White shirt**
Test #:	**1**	Inner garment:	**White undershirt**
Mannequin location:	**40 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin:	**Male**		
Radiometer view:	**Inner radiometer on the chest**	Other Data:	None
	View through button flap on outer shirt		

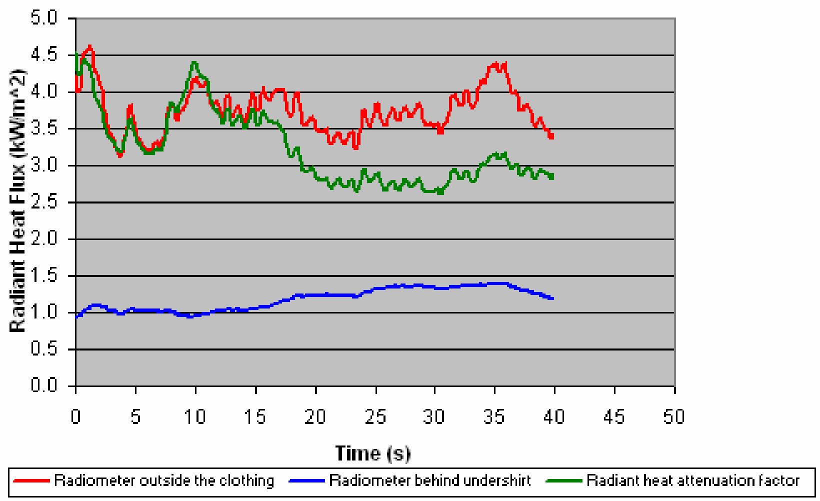
Double layer clothing

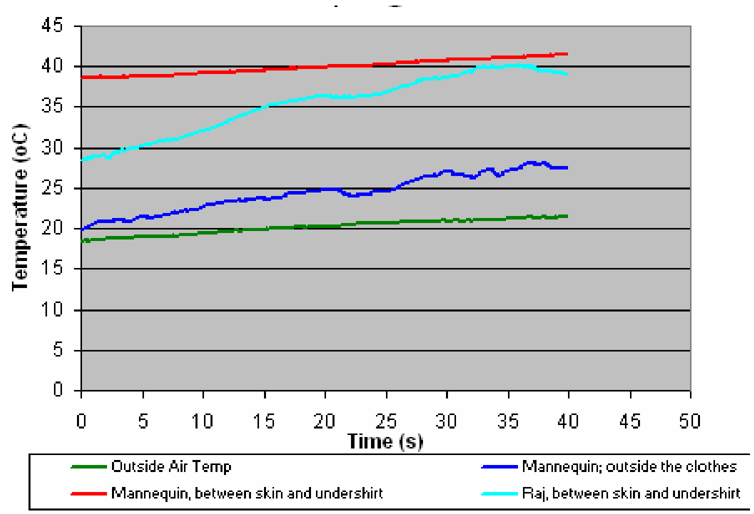




Test Date:	**10/05/2006**	Outer garment:	**White shirt**
Test #:	**2**	Inner garment:	**White undershirt**
Mannequin location:	**40 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin**:**	**Male**		
Radiometer view:	**Inner radiometer on the chest**	Other Data:	None
	View through button flap on outer shirt		

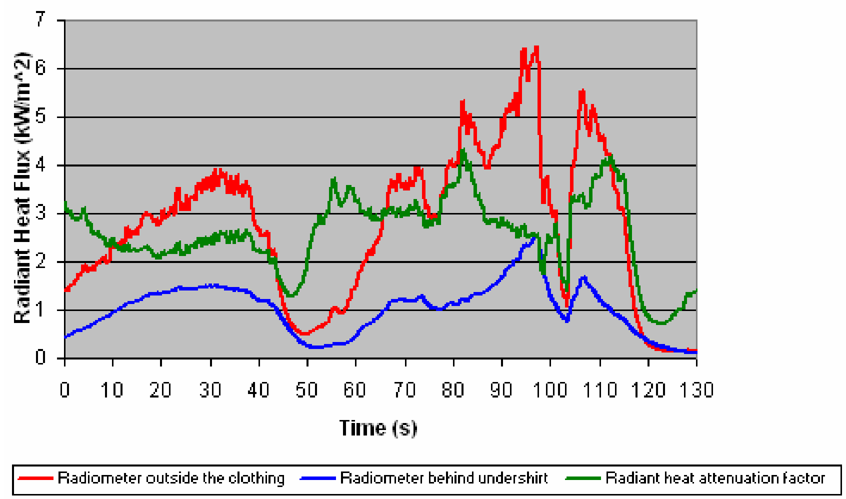
Double layer clothing

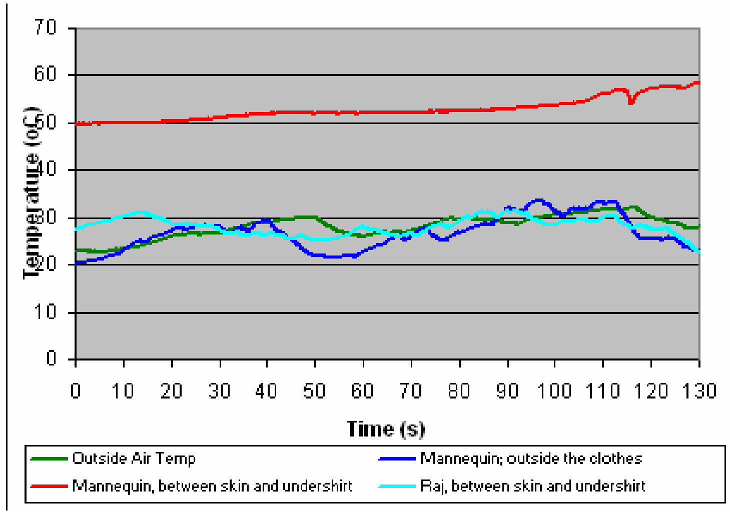




Test Date:	**10/05/2006**	Outer garment:	**White shirt**
Test #:	**3**	Inner garment:	**None**
Mannequin location:	**40 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin**:**	**Male**		
Radiometer view:	**Inner radiometer on the chest** **View through button flap on outer shirt**	Other Data:	None

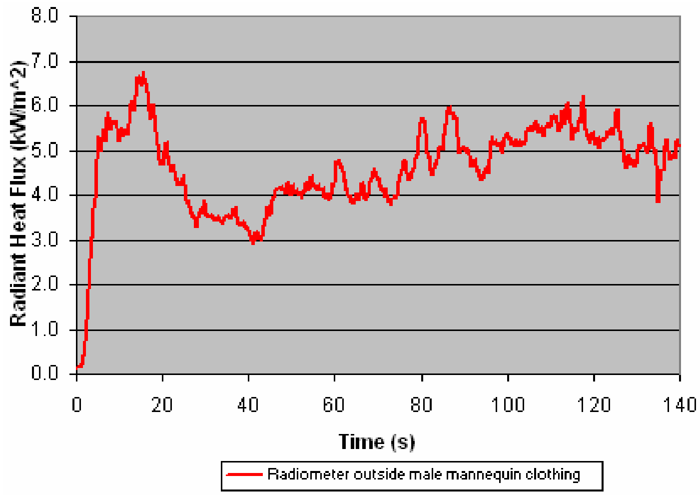
Single layer clothing

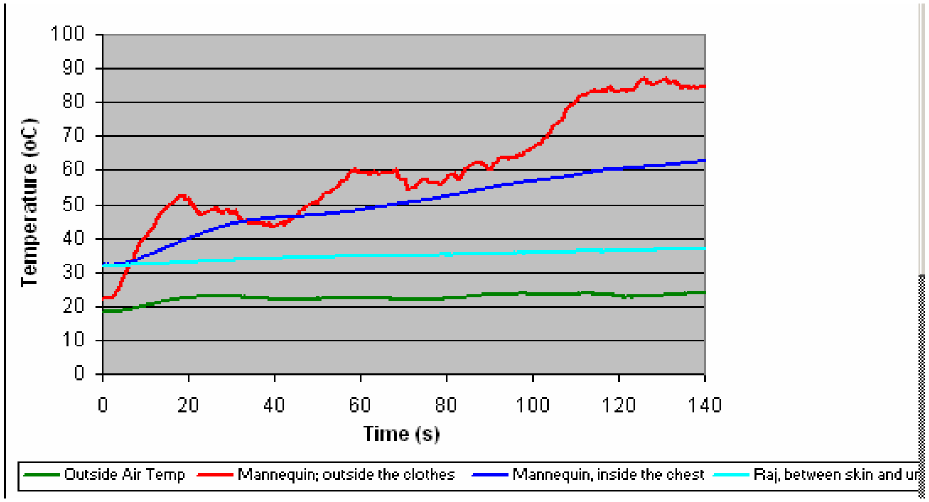




Test Date:	**10/19/2006**	Outer garment:	**White shirt**
Test #:	**1**	Inner garment:	**White undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin**:**	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	**Inner radiometer data lost**

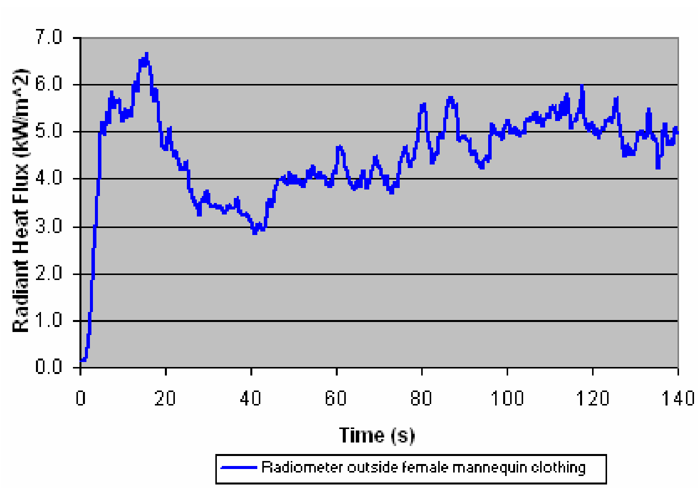
Double layer clothing

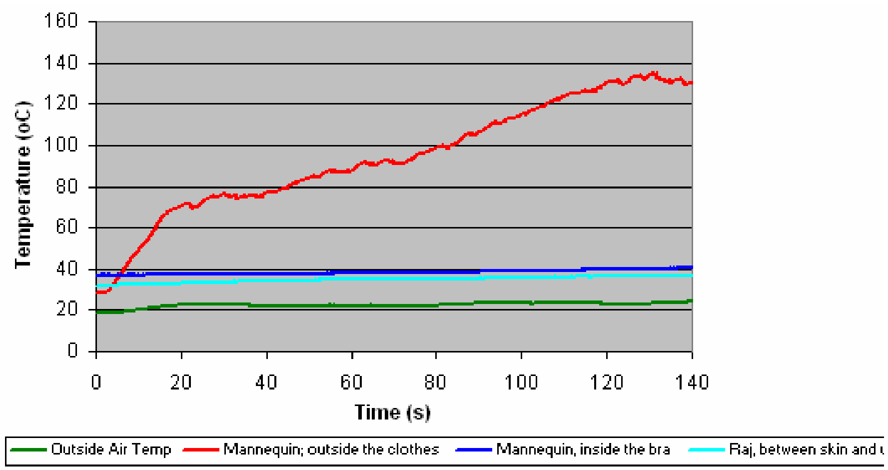




Test Date:	**10/19/2006**	Outer garment:	**Red shirt**
Test #:	**1**	Inner garment:	**Green undershirt**
Mannequin location:	**40 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin**:**	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	**Inner radiometer data lost**

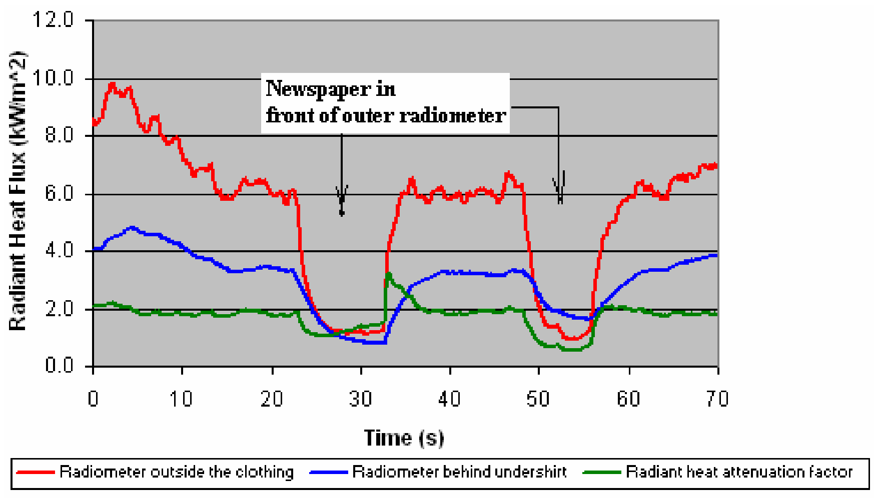
Double layer clothing

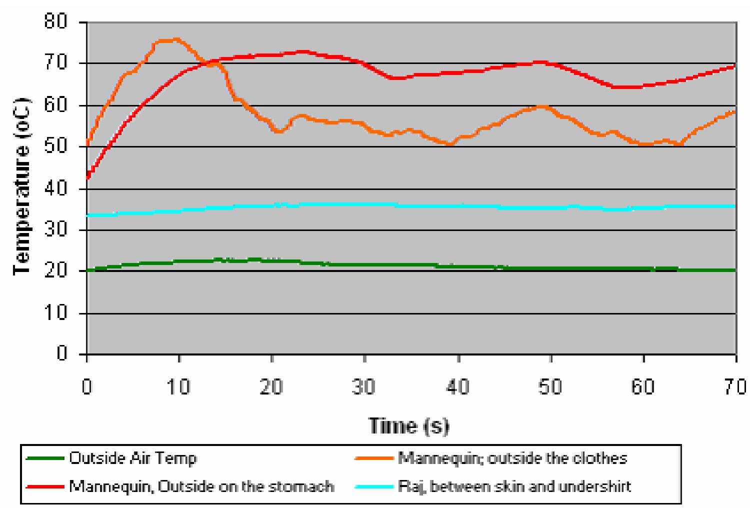




Test Date:	**10/19/2006**	Outer garment:	**Not used**
Test #:	**2**	Inner garment:	**White undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin:	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	**Newspapers of single and double sheet thickness interposed**

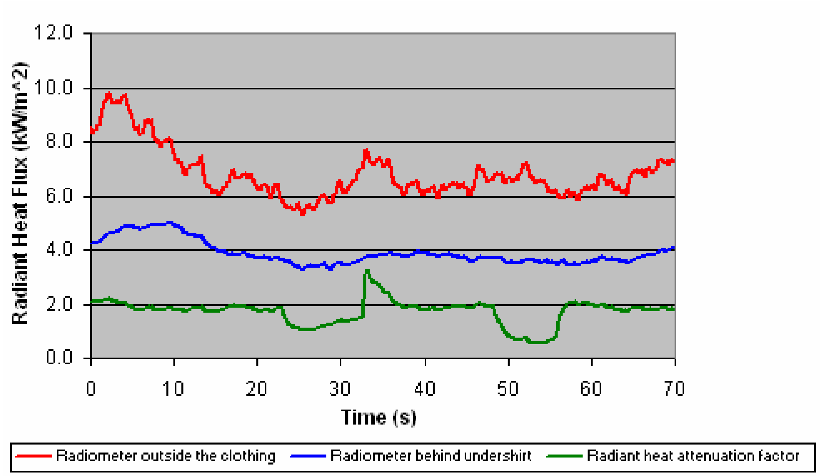
Single layer clothing

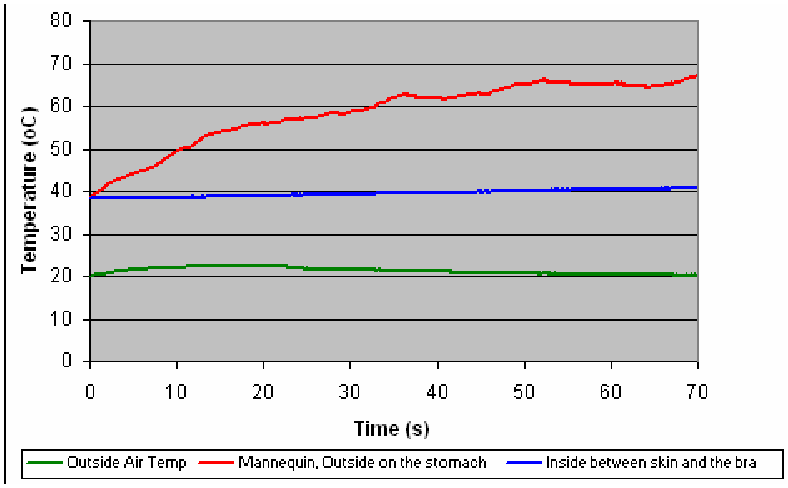




Test Date:	**10/19/2006**	Outer garment:	**Not used**
Test #:	**2**	Inner garment:	**Green undershirt**
Mannequin location:	**40 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin**:**	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	

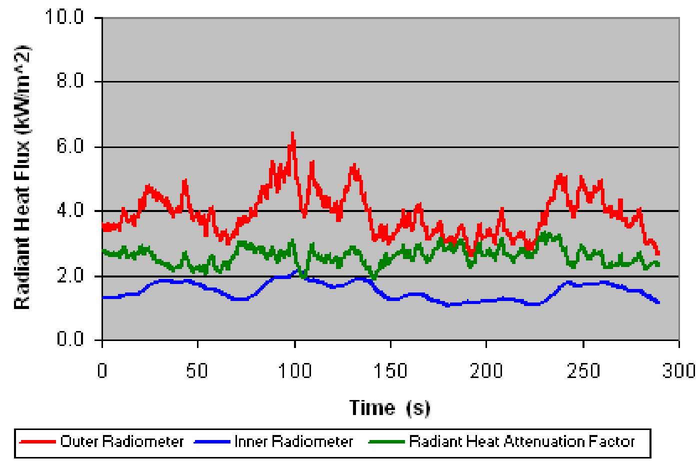
Single layer clothing

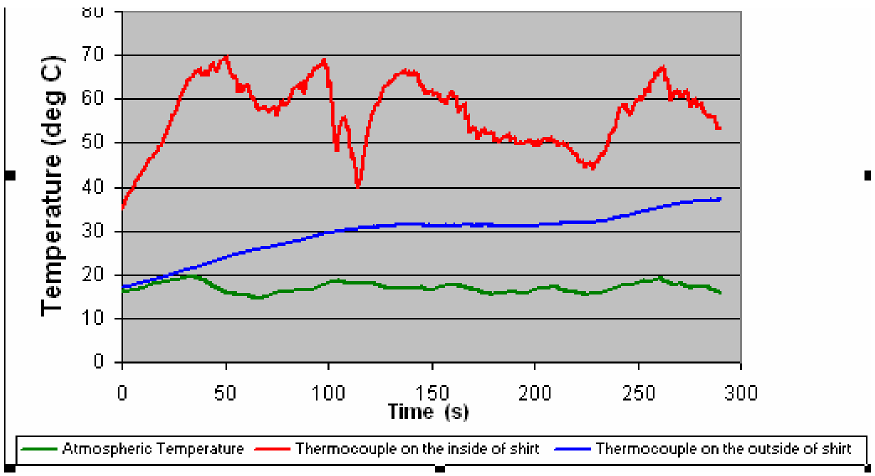




Test Date:	**10/21/2006**	Outer garment:	**White shirt**
Test #:	**1**	Inner garment:	**White undershirt**
Mannequin location:	**31 ft from fire center**	Clothing fit:	**Slightly tight**
Type of mannequin:	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	Thin cloth layers in series

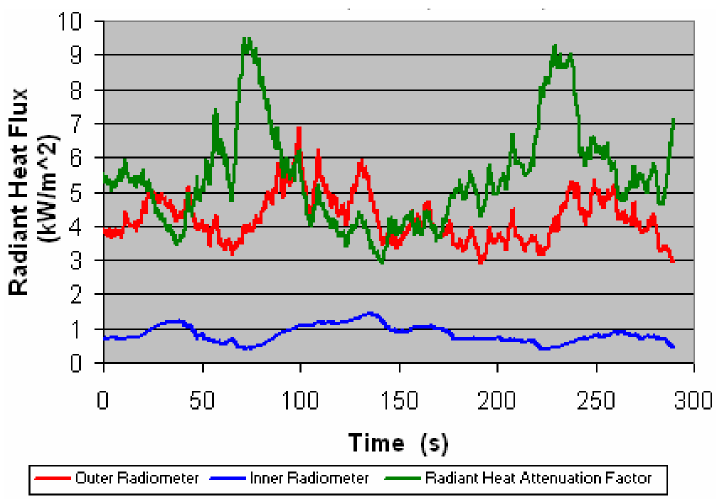
Double layer clothing (thin part of clothing layers in series)

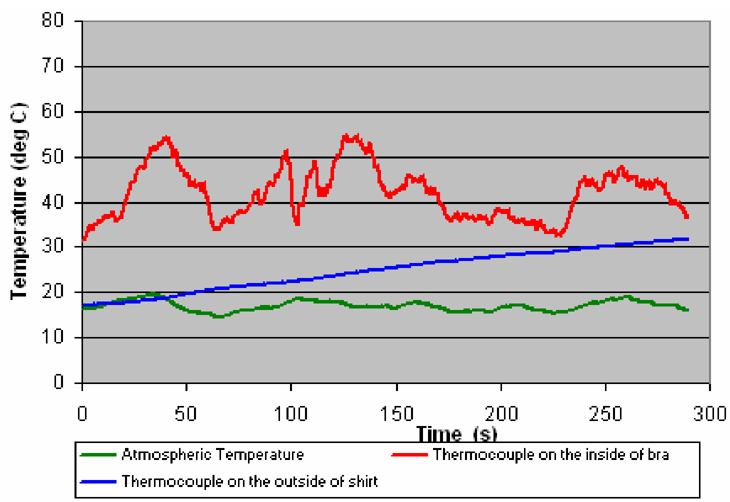




Test Date:	**10/21/2006**	Outer garment:	**Red shirt**
Test #:	**1**	Inner garment:	**Green undershirt**
Mannequin location:	**31 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin:	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	**Inner radiometer view thro button flap**

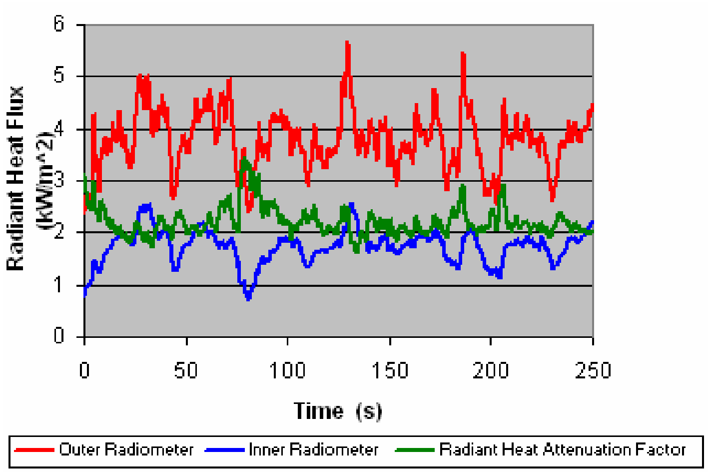
Double layer clothing

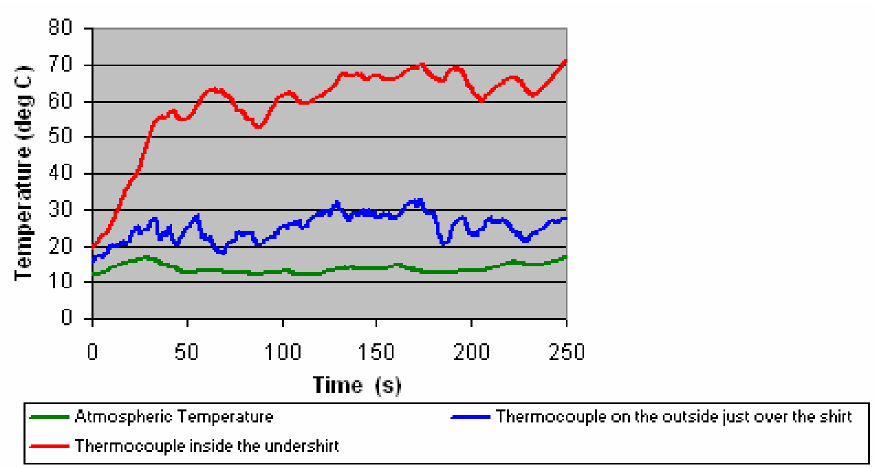




Test Date:	**10/21/2006**	Outer garment:	**None used**
Test #:	**2**	Inner garment:	**White undershirt**
Mannequin location:	**31 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin**:**	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	Thin cloth layers in series

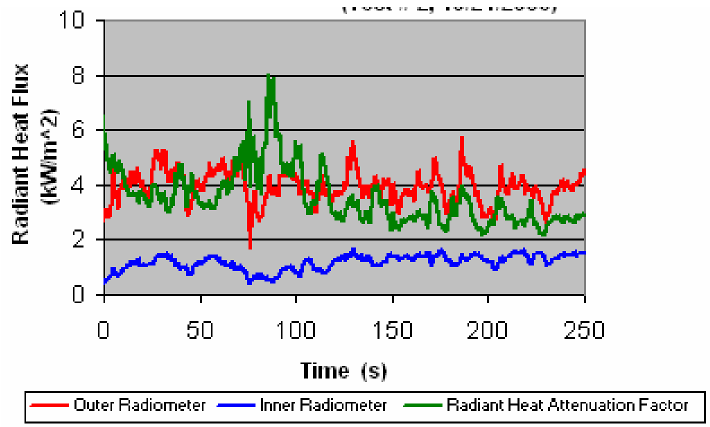
Single layer clothing (undershirts only used)

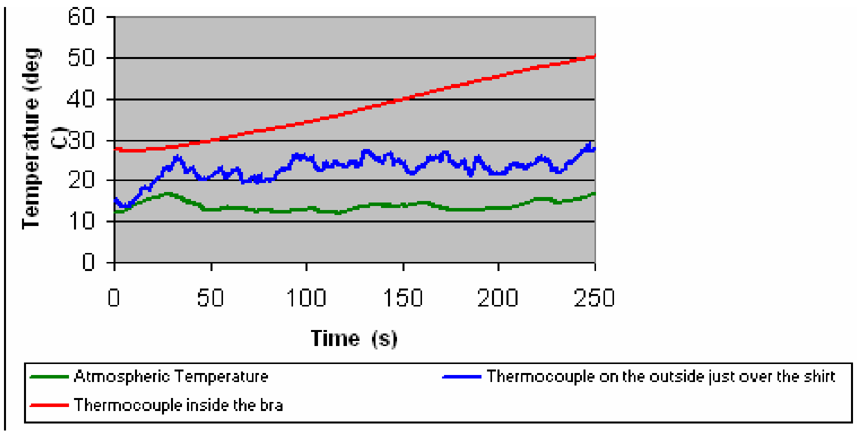




Test Date:	**10/21/2006**	Outer garment:	**None used**
Test #:	**2**	Inner garment:	**Green undershirt**
Mannequin location:	**31 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin:	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	

Single layer undershirt clothing

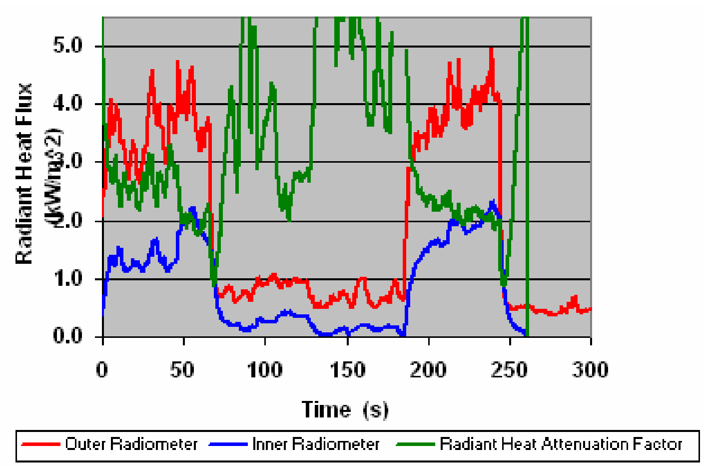


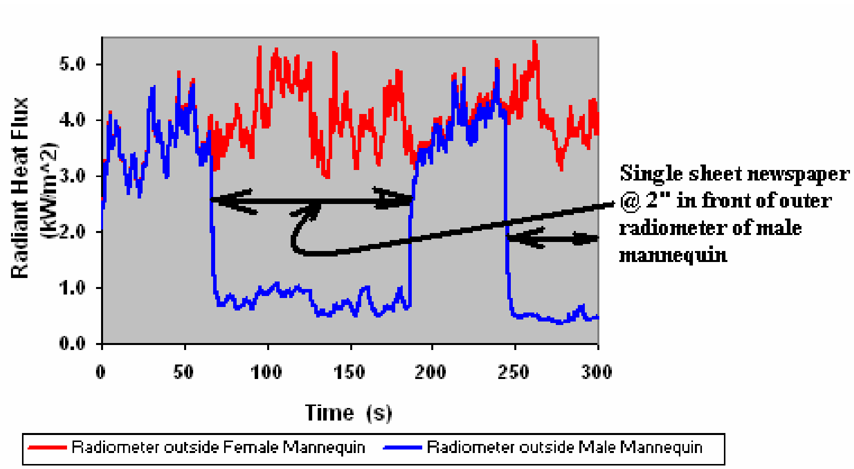


Test Date:	**10/21/2006**	Outer garment:	**None used**
Test #:	**3**	Inner garment:	**White undershirt**
Mannequin location:	**31 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin:	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	Thin cloth layers in series

Single layer clothing (undershirts only used)

Effect of placing a newspaper at 2" in front of the outer radiometer studied

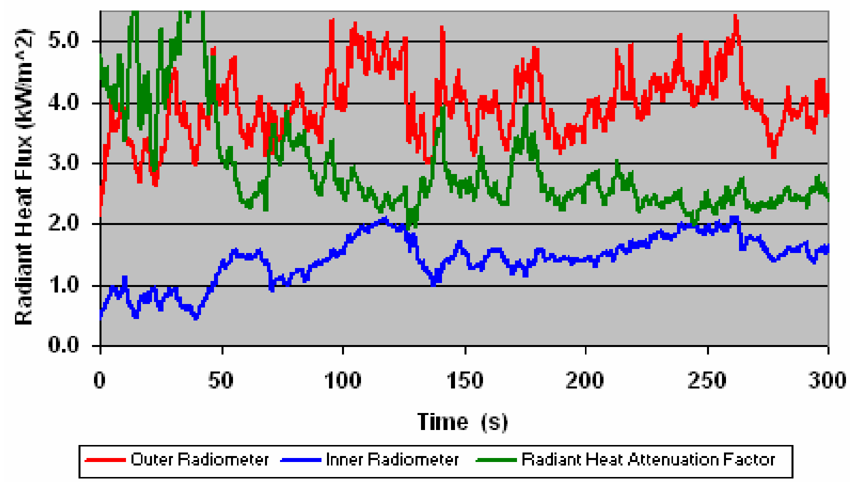




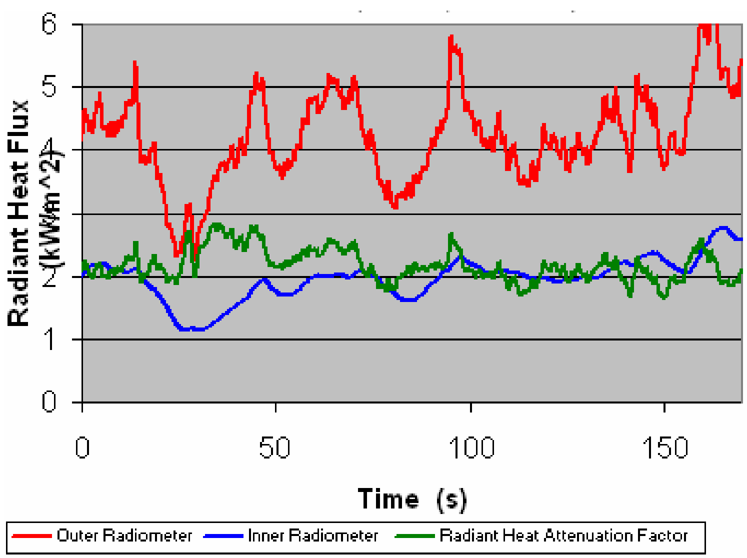
Test Date:	**10/21/2006**	Outer garment:	**None used**
Test #:	**3**	Inner garment:	**Green undershirt**
Mannequin location:	**31 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin:	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	

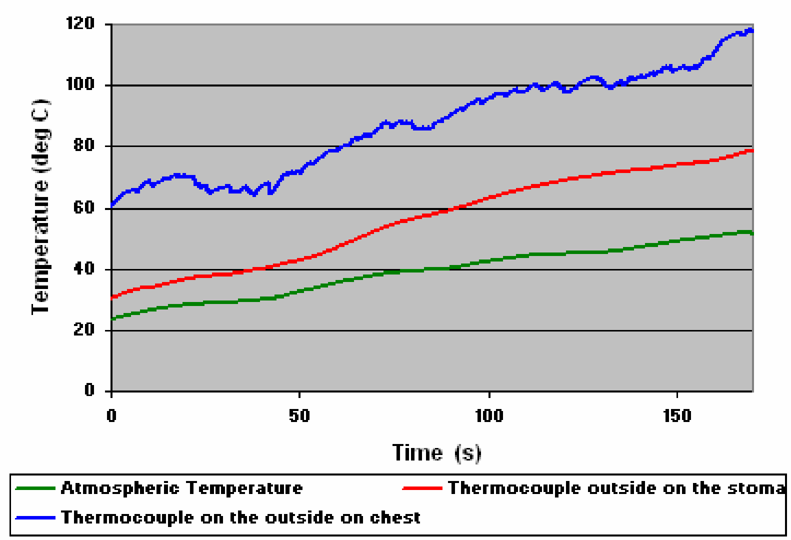
Single layer undershirt clothing

(Inner radiometer probably looking through the thick collar of undershirt)



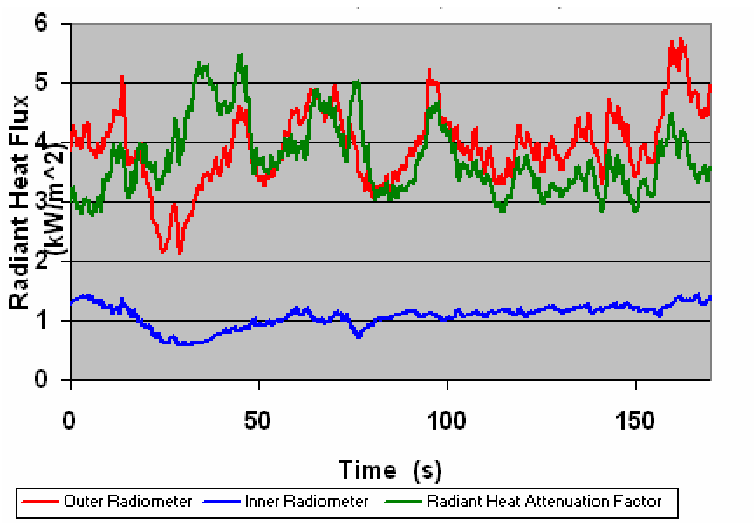
Test Date:	**11/02/2006**	Outer garment:	**White shirt**
Test #:	**1**	Inner garment:	**White undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin:	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	None
	Male mannequin inner radiometer looking through two layers of thin clothing		
	Double layer clothing		

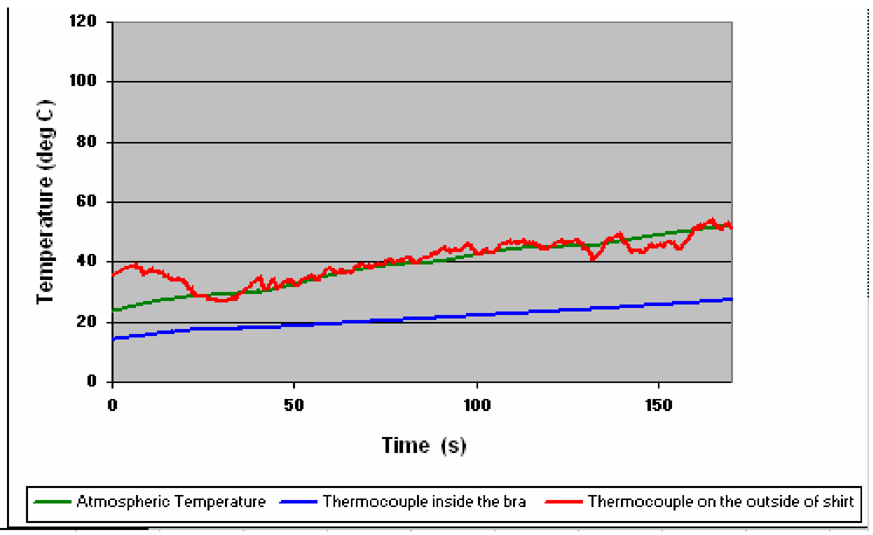




Test Date:	**11/02/2006**	Outer garment:	**Red shirt**
Test #:	**1**	Inner garment:	**Green undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin:	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	None
	Inner radiometer looking through collar thick cloth		

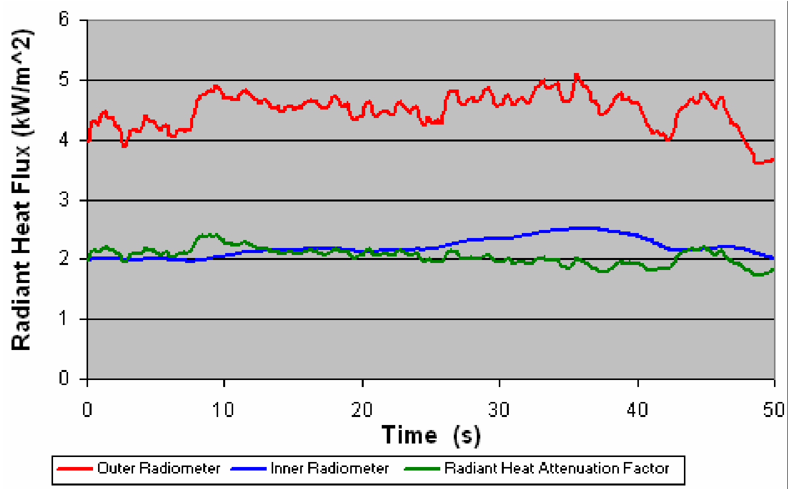
Double layer clothing

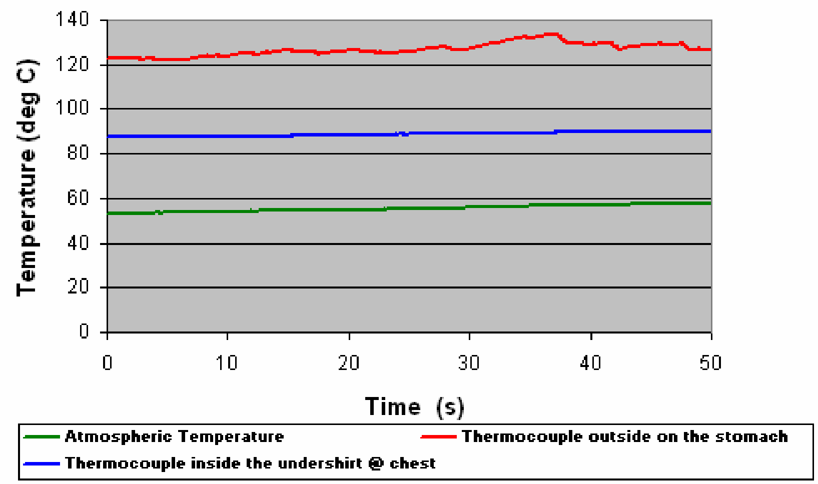




Test Date:	**11/02/2006**	Outer garment:	**White shirt**
Test #:	**2**	Inner garment:	**White undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin:	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	None
	Male mannequin inner radiometer looking through two layers of thin clothing		

Double layer clothing

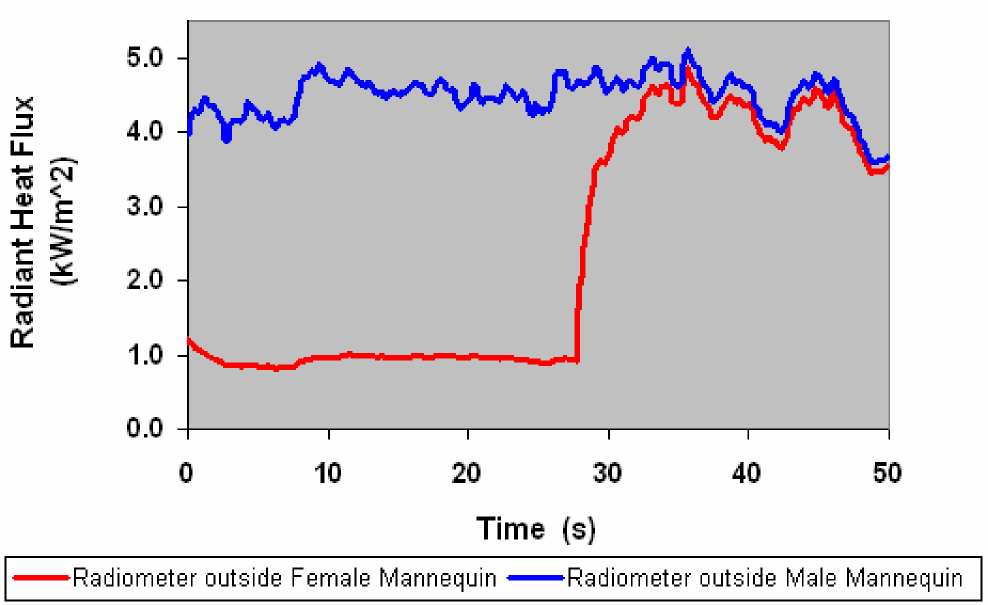




Test Date:	**11/02/2006**	Outer garment:	**Red shirt**
Test #:	**3**	Inner garment:	**Green undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin**:**	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	None
	Inner radiometer looking through collar thick cloth		

Single sheet newspaper interposed between fire and outer radiometer at 2“

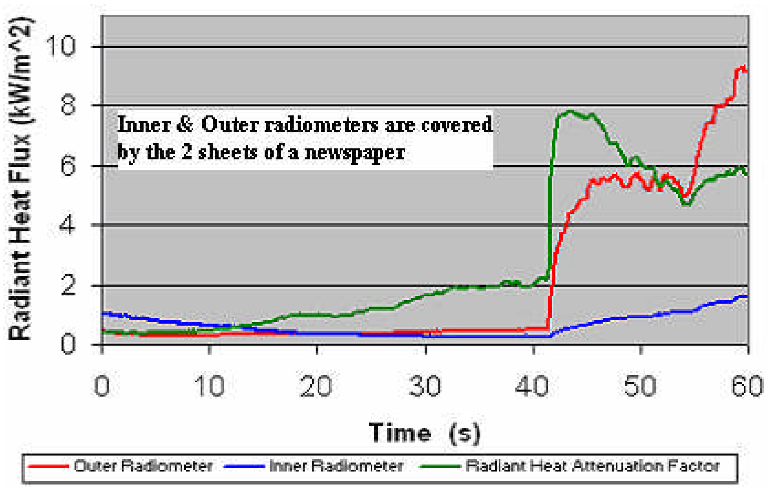
Double layer clothing

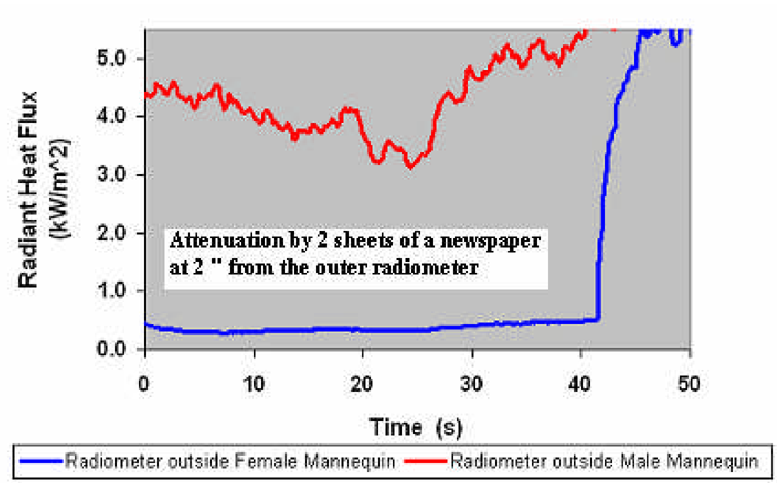


Test Date:	**11/02/2006**	Outer garment:	**Red shirt**
Test #:	**3**	Inner garment:	**Green undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin:	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	None
	Inner radiometer looking through collar thick cloth		

Two sheets of a newspaper interposed between fire and outer radiometer at 2“

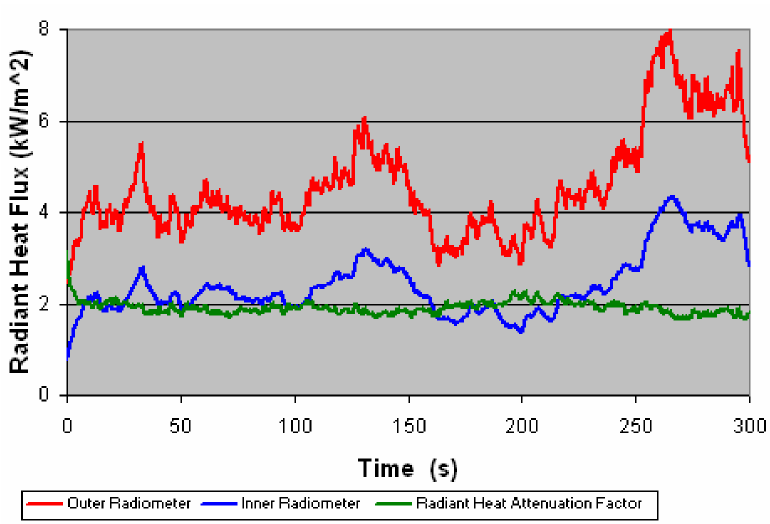
Double layer clothing

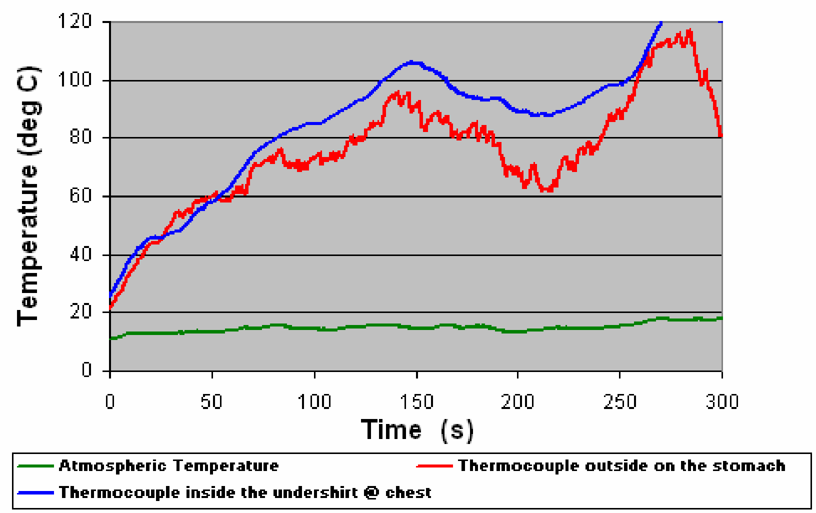




Test Date:	**11/02/2006**	Outer garment:	**None used**
Test #:	**4**	Inner garment:	**White undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Loose**
Type of mannequin**:**	**Male**		
Radiometer view:	**Radiometers at chest level**	Other Data:	

Single layer clothing (undershirts only used)



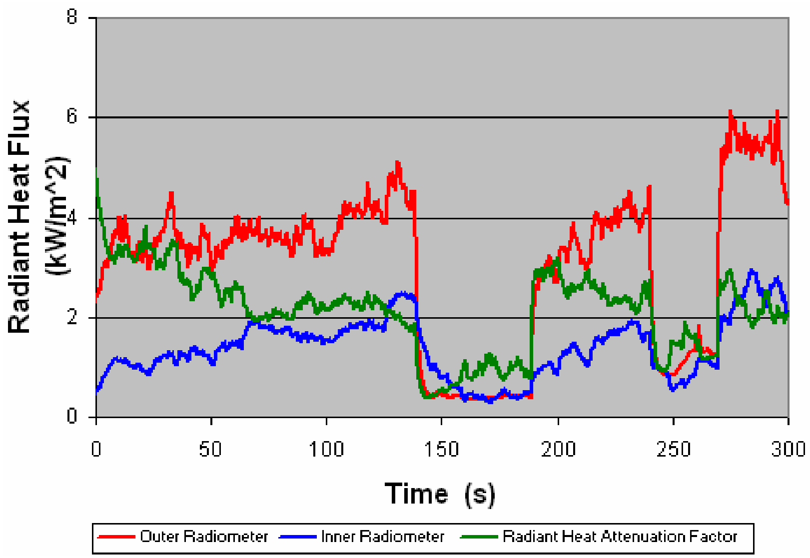


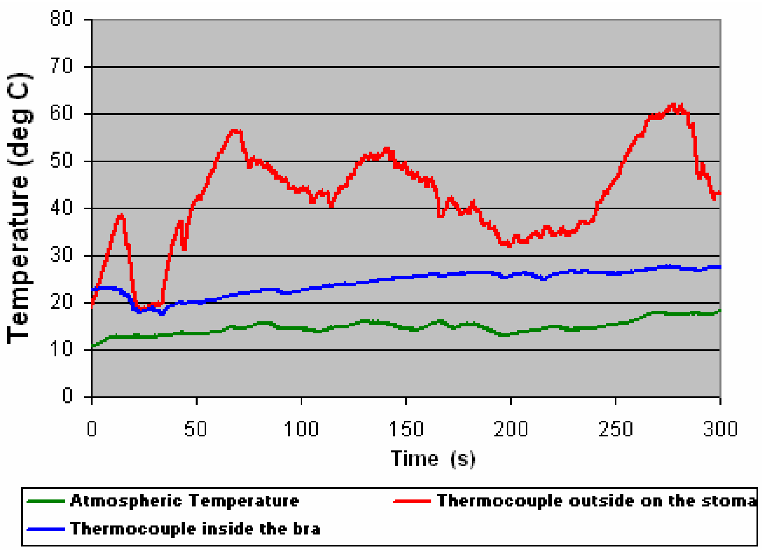
Test Date:	**11/02/2006**	Outer garment:	**None used**
Test #:	**4**	Inner garment:	**Green undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin**:**	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	

Single layer undershirt clothing

(Inner radiometer looking through the thick collar of undershirt)

<u>Effect of placing a newspaper at 2" in front of the outer radiometer studied</u>



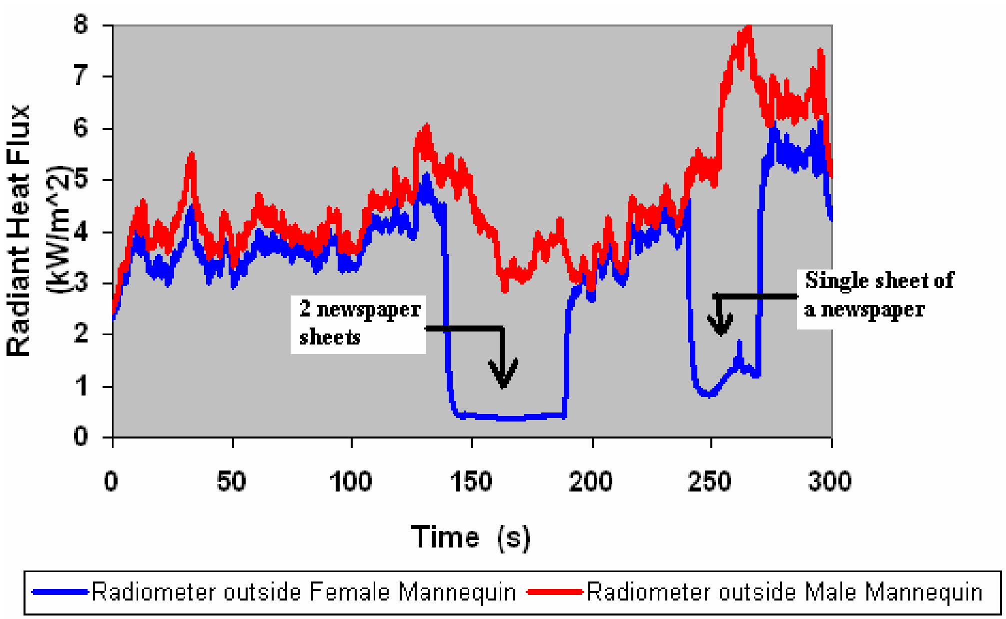


Test Date:	**11/02/2006**	Outer garment:	**None used**
Test #:	**4**	Inner garment:	**Green undershirt**
Mannequin location:	**30 ft from fire center**	Clothing fit:	**Tight**
Type of mannequin**:**	**Female**		
Radiometer view:	**Radiometers @ chest level**	Other Data:	

Single layer undershirt clothing

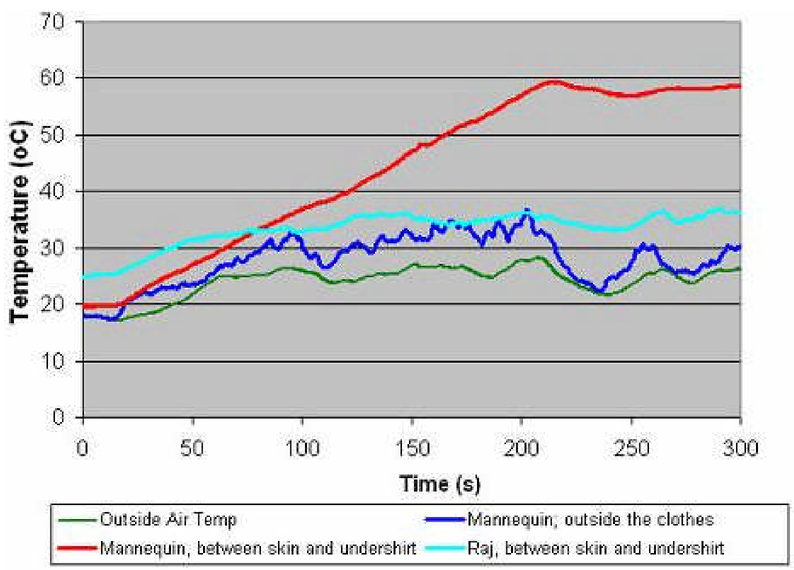
(Inner radiometer looking through the thick collar of undershirt)

<u>Effect of placing a newspaper at 2" in front of the outer radiometer studied</u>

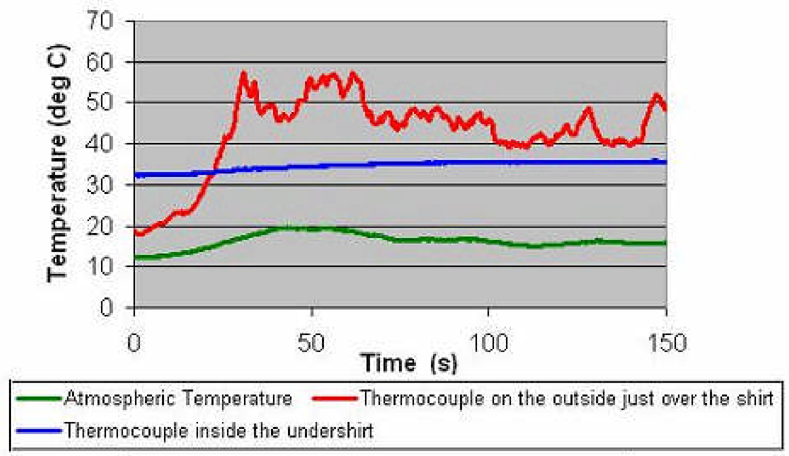


C.2: Data from the tests involving human exposure to LNG fire radiant heat

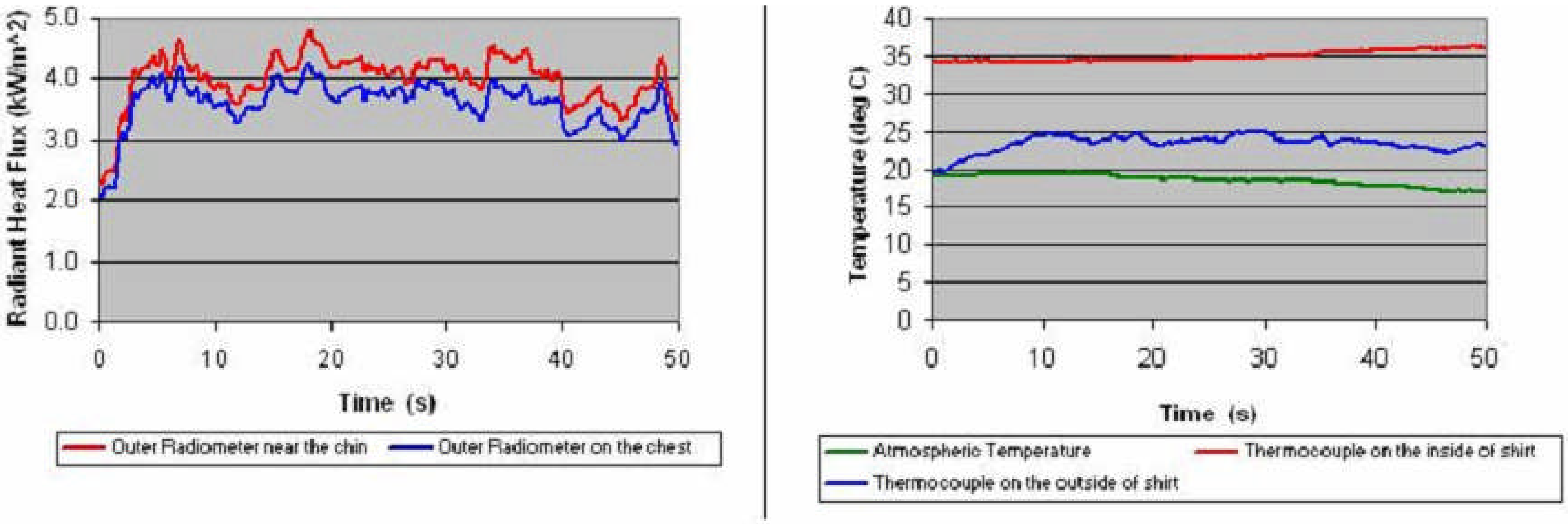
The project manager and author of this report, Dr. Phani Raj, was the human subject for the tests results reported here. He was exposed to the LNG fire radiant heat wearing only civilian clothes. Two Medtherm radiometers (wide-angle) were strapped on to the subject to measure the radiant heat flux incident on the subject, outside the clothing. Thermocouples were placed at (i) inside between the skin and the undershirt (once on the belly and other times on the chest), (ii) just outside the outer shirt (bead almost touching the shirt) and (iii) one measurement of the temperature of the air in front of the subject. The following are the recorded data from the radiometers and thermocouples.



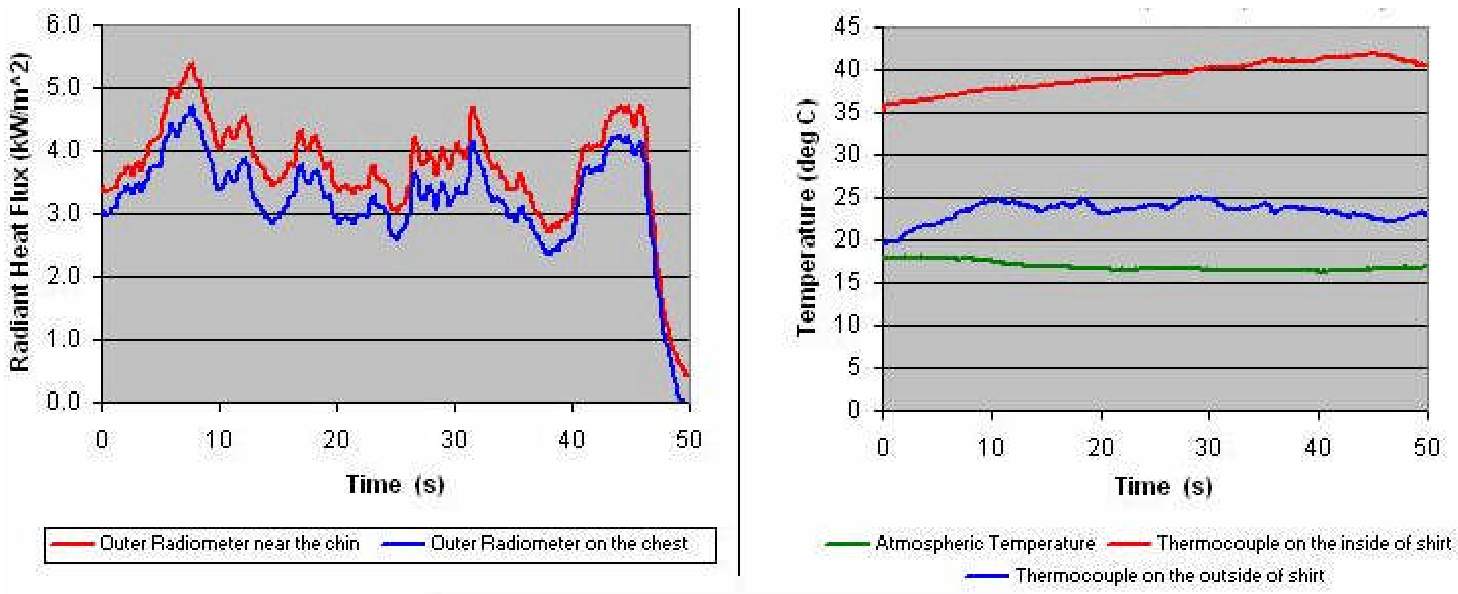
Temperature measurments on male mannequin and on the human subject.
Test # 1, 10/05/2006, Location of subjects: 40 ft. from fire center



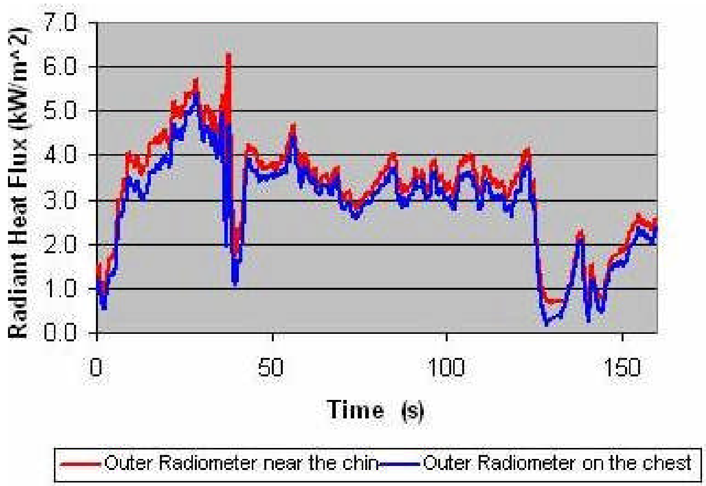
Double layer clothing; Test # 1, 10/21/2006,
Subject location 25 - 32 ft from fire center

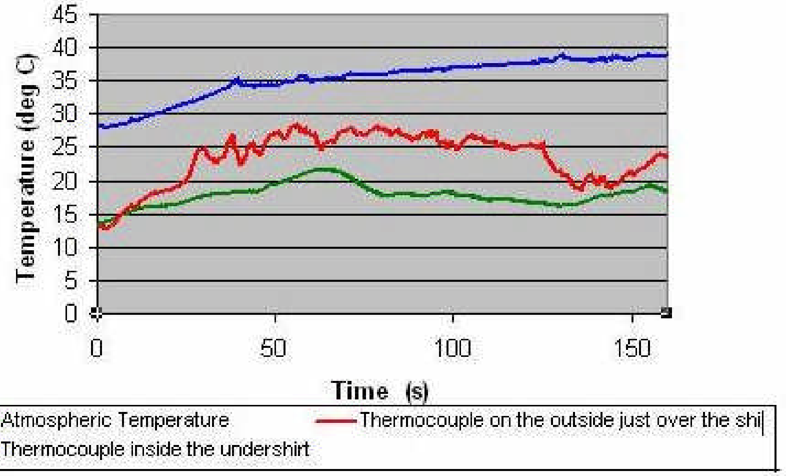


Double layer clothing; Test # 2, 10/21/2006,
Subject location 25 - 32 ft from fire center



Double layer clothing; Test # 3, 10/21/2006,
Subject location 25 - 32 ft from fire center





Double layer clothing Test # 5, 11/02/2006, Subject location 25 - 32 ft from fire center